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Signal analysis of wind turbine acoustic noise

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Tuuliturbiinien määrä lisääntyy Suomessa. Tuulipuiston rakentamisen edellytyksinä ovat suotuisat tuuliolosuhteet ja tarpeeksi suuri vapaa alue. Asutuskeskuksien ulkopuolella kuitenkin esiintyy yksittäisiä asuntoja, joiden takia turbiineista lähtevä melutaso ei saa ylittää määrättyjä raja-arvoja.

Turbiinin tuottaman melu mitataan, jotta voidaan varmistaa vaadittujen tasojen alitus. Viimeisin standardi tuuliturbiinimelun analysoimiseksi on IEC 61400-11. Tässä diplomityössä on määritelty turbiinin tuottama kapeakaistaisen melun kuuluvuus standardin avulla.

Taustamelun energian jakautuminen tasaisesti kriittisen kaistan leveydelle on edellytys laskennan onnistumiselle. Jos vaihtelevuus taajuuspiikkien välillä on suurta analyysitapa löytää ääneksiä taustamelusta. Laskentamalli sallii yksittäisen ääneksen taajuusvaihtelun 10 sekunnin pituisten näytteiden välillä. Tämä mahdollistaa kapeakaistaisuuden löytymisen, vaikka sen kuuluvuudesta ei ole varmuutta.

Avainsanat: Melu, akustinen mittaus, melun mittaus, signaalianalyysi, signaalinkäsittely, kapeakaistaisuus, tuuliturbiini

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ABSTRACT OF THE MASTER'S THESIS

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In Finland wind turbines are becoming more common. Wind farms are built outside residential concentrations where wind conditions are strong enough for power production. Even though the locations are remote, turbines are sometimes erected near dwellings and therefore the generated noise emissions have to meet certain threshold levels.

In order to ensure that the required noise levels do not exceed the limits, measurements have to be done. The most recent standard for wind turbine noise analysis is IEC 61400-11. In this thesis the tonal audibility of a turbine is assessed by the means of the standard.

The analysis method requires background noise to have a steady frequency distribution of energy within a critical band. Otherwise the calculations reveal single tones generating from the background noise. Variation of frequency between consecutive 10 second sections of the acquired signal is allowed, which makes it possible for tones with questionable audibility to be reported.

Keywords: Acoustic noise, acoustic measurements, noise measurements, signal analysis, signal processing, narrowband, wind turbines

Preface

I would like to thank Tuuliwatti Oy for giving me the opportunity to write this thesis. Measurements at the wind farm have been highly educational.

Thanks to Carlo Di Napoli for all the help and support during the frustrating hours spent solving problems. Also I would like to thank my supervisor Vesa Välimäki.

This thesis concludes a magnificent era of my life. Every experience during my years at universities in Finland and in Sweden have proved that engineering is not the easiest path to success. Still I would not change a day.

Otaniemi, 22.11.2014

Panu Lehto

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Symbols and abbreviations

Symbols

Bc	critical band
Bn	effective noise bandwidth
c_0	speed of sound
F	force
f	frequency
f_a	analysis frequency
f_c	centre frequency of a band
f_l	lower frequency limit
f_{max}	frequency of a tone maximum
f_{res}	frequency resolution
f_s	sampling frequency
f_u	upper frequency limit
h	thickness
i	number of spectrum
j	imaginary unit
k	penalty
L_{Aeq}	A-weighted equivalent noise level
L_p	sound pressure level
L_pn	sound pressure level of noise
L_pt	sound pressure level of tone
L_w	sound power level
M	Mach number
N	length in samples
p	pressure
p_0	reference pressure
r	distance
t	time
U	effective flow speed
U_r	rotational flow speed
U_w	wind speed
$X(f)$	continuous time-domain signal
α	angle of attack
Δf	varitation in frequency
ΔL_a	tonal audibility
ΔL_{tn}	audibility
$\Delta L_{tn,crit}$	criterion level
θ	angle
Λ	length-scale of an eddy
λ	wavelength
ω_h	Hanning window function
ω_r	rectangular window function

Abbreviations

FFT	Fast Fourier Transform
DFT	Discrete Fourier Transform
ETSU	Energy Technology Support Unit
EU	European Union
HAWT	Horizontal-axis wind turbine
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
jnd	just-noticeable difference between two nearly equal auditory stimuli
JNM	Joint Nordic Method
jnvf	just-noticeable variation in frequency
PSD	Power Spectral Density
WT	wind turbine

1 Introduction

In Finland there are vast forest areas along the coastline that could be considered as good locations for wind farms. Secluded holiday houses require a lower noise limit, which limits the use of possible sites. It has become increasingly important to reduce the level of created noise, for the turbines might end up locating quite near dwellings.

The current energy strategy states that the amount of renewable energy production should reach 38 % out of entire production of the country by the year 2020. Also reduction of emissions is required by the EU. [1]

Wind power is still a little used way of producing electricity in Finland. In August 2012 there were only 145 turbines with overall capacity of 234 MW, but the amount needs to be increased in order to reach the goal by the deadline [2]. Production goal is set to 9 TWh by 2015 [1].

Sound waves have a tendency to be attenuated when encountering a barrier on the propagation path. Industrial grade turbines are usually remarkably high and located on flat areas, so there are usually no objects limiting the spread of noise.

Measuring noise emissions in strong wind conditions is challenging. The procedure differs from common environmental noise surveys. Because of the wind, the background noise levels are high. The generated power and noise change with the wind speed. The noise can be described as narrow band, impulsive and amplitude modulated. The produced noise varies much in time. Assumption is that the turbine's noise emissions are at highest when it is working at its nominal power. [3]

Annoyance is one of the biggest issues concerning noise emission from wind turbines. It is experienced as disruptive as flight noise of the same sound level. But road noise of the same level is considered to be a little less annoying. [4]

Some parameters of sound may enhance the perception and annoyance [5]. Tonality is one of them. The perceived level of tonal noise is dependent upon the attitude and sensitivity of the listener towards the noise source and its characteristics [6]. Also the ability to see the sound source could affect the experienced annoyance [7].

Tonality could lead to penalty in measured noise levels, thus causing the threshold level to be exceeded. Which could lead to usage of noise modes that bring the emission level down, but also leads to lowered power production. Too severe reduction would lead to the farm being unprofitable.

Wind turbines generate noise that can be divided into two categories: mechanical and aerodynamic. Tonal noise is usually caused by the mechanical components but also vortices induced by the turbine blades are a possible source. Narrow band noise does not make a large contribution to the overall sound pressure level, but due to its psycho-acoustic importance it needs to be taken into account when defining the impact of noise emissions. The most recent standard for assessing whether tonal noise is audible or not is called IEC 61400-11. In this thesis the calculations and signal analysis methods are reviewed and applied on a 4.5 MW turbine.

In section two the fundamentals of wind turbine noise generation mechanisms are explained. Also the most important factors in sound attenuation concerning environmental noise are presented. In section three signal analysis methods used in the narrow band noise calculation method are introduced. In section four the concept of tonality and psychoacoustic characteristics of human perception of sound are given. In section five analysis method of IEC 61400-11 is explained step by step. In addition some key features of other similar standardised tonality calculation method are presented. In section six the measurement procedure of a wind turbine is explained, which is followed by the results of the tonality assessment. In section seven this work is summarised and encountered problems are discussed.

2 Basics of wind turbine acoustic noise

Sound becomes noise when it is unwanted. A high sound pressure level is not the only cause of the unpleasantness. The effect on people is categorised into subjective and physiological effects. Subjective effects are for example annoyance, intereference with activities such as speech and physiological effects are actual hearing damage or anxiety. When considering wind turbines only the subjective are of concern. [8]

The experienced disturbance is influenced by many factors. For example the location of the observer relative to the turbine and wind direction has to be taken into account. Also the environment with natural and man made obstacles make their contribution to the sound landscape. Though, the actual turbine type and its characteristics must not be forgotten. [9]

A wind turbine can generate four kinds of noise: tonal, broadband, low-frequency and impulsive. Tonal noise is caused by components such as meshing gears, airflow around the blade including boundary layer instabilities and unstable flows over holes and slits or by vortex shedding from a blunt trailing edge. Broadband noise is often caused by interaction of the blades with atmospheric turbulence. Low-frequency noise is mostly associated with downwind turbines. [10]

In this section the generation of sound emitted from different parts of wind turbines are presented. In general the noise generated by wind turbines is divided into two groups by source mechanism: mechanical and aerodynamic noise. The latter is dominating with noise emitted from the blades.

2.1 Design of a wind turbine

Conventional horizontal-axis wind turbines (HAWT) consist of three main components: a rotor, a generator and a tower. All of the generating components are situated inside a cover called nacelle and the rotor is situated on the upwind side on most contemporary turbines. The wind by interaction with the rotor blades is transformed into rotational energy and furthermore into electricity with the generator. With a gearbox the slow rotation of the rotor is converted to high speed rotation that is suitable for generating electricity.

2.2 Mechanical noise

Mechanical noise originates from different moving components of the machinery. Such are the gearbox, the generator, yaw and pitch actuators, cooling fans and hydraulic systems. Due to the relative motion of the mechanical components and dynamic response among them, emissions tend to be tonal, although broadband components may occur. In Finland this leads to a penalty of 5 dB, which is added to the measured value [11]. Even with lower level, tonality causes more annoyance than broadband noise.[8][12]

There are two transmission paths for the noise. Air-borne means that the sound propagates directly from the component surface or interior into the air. Structure-borne means that the noise is transmitted from the source via structural connections before it is radiated by an other component. These parts are working as a loudspeaker. In figure 1 are shown the contribution of individual components to the total sound power level for a 2 MW wind turbine. [8][12]

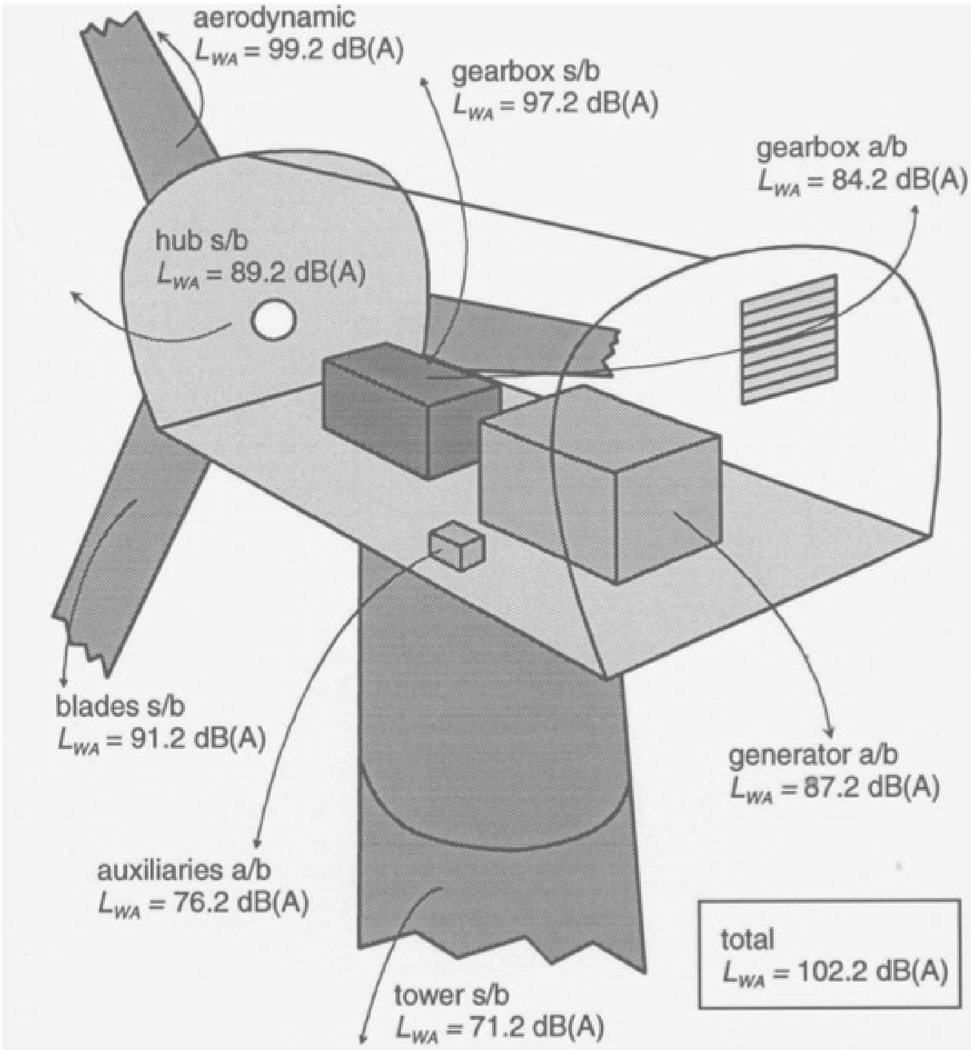


Figure 1: Components' contribution to the total sound power level [12]

The mechanical noise mainly originates from the gearbox and is radiated by the surfaces of the nacelle and the machine raft. It is caused by vibrations and loading started by imperfections in the gear pitch and form of the meshing teeth. As said vibrations are transmitted into the surrounding parts of the nacelle, tower or the blades via the bearings of the gear box. Thus vibration isolation between mechanical parts and the nacelle could result in significant noise reduction. Damping of transmission paths and including flexible couplings between nacelle casing parts are an example of possible improvement actions. [9][12]

Even though elements such as fans, inlets, outlets and ducts generate mainly noise of aerodynamic nature they are listed as mechanical sources. Cooling fan has interaction between moving and fixed parts. The spectrum of the noise has a broadband component because of air turbulence and pure tones that are harmonics of the rotating frequency. [9]

Unlike with mechanical noise, the spectrum of aerodynamic noise is typically smooth due to its broadband nature. Mechanical components produce a number of substantial tones and side bands because of meshing or rotation frequency harmonics. A typical spectra of machinery induced noise are presented in figures 2 and 3.

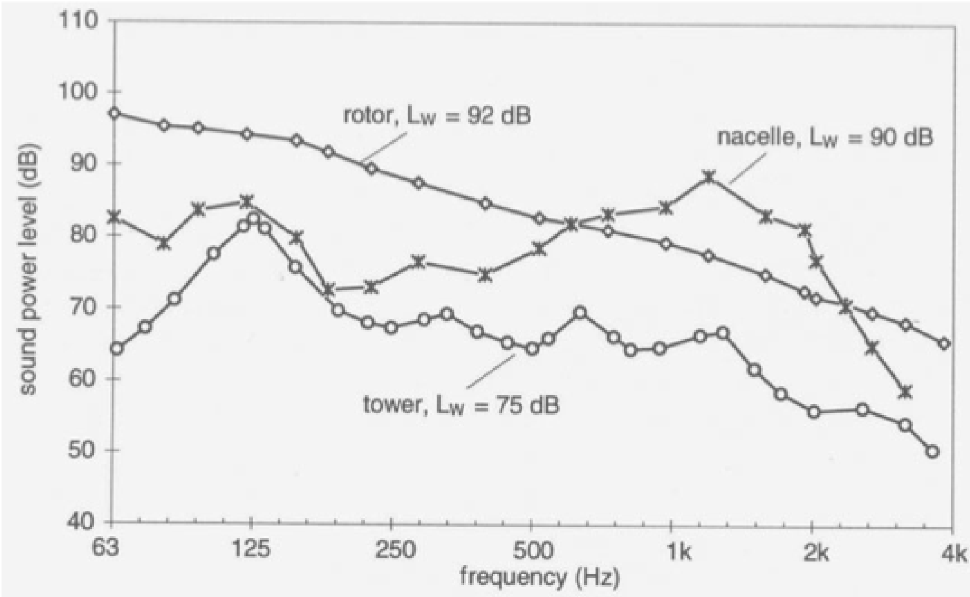


Figure 2: Components contribution magnitudes to sound pressure level [12]

The size of the turbine does not increase the mechanical noise as fast as it does for aerodynamic [13]. [12]

Tonality is possible to control with certain frequencies, but if the rotation speed is not constant, the prequisities for vibration control change with the speed.

2.3 Air flow

For a modern large wind turbine aerodynamic noise is commonly considered to be the dominant noise source. This assumption of course requires that mechanical noise is properly treated. Blade noise also increases faster than noise emitted from the hub with rising wind speed. [14]

Aerodynamic noise is caused by the flow of air around the rotor blades. The flow is caused by the wind and the rotation of the rotor. For most modern turbines the rotation is anti-clockwise, when observed from a downwind position (figure 4). Thus the effective flow speed U perceived by the blade is a combination of the wind speed U_w and the rotational flow speed U_r (figure 5). The typical rotational speed of the blade tip is 75 m/s, while the wind speed at rotor height is around 10 m/s. The form of the blade's cross section (airfoil) is designed for diverting the incoming flow

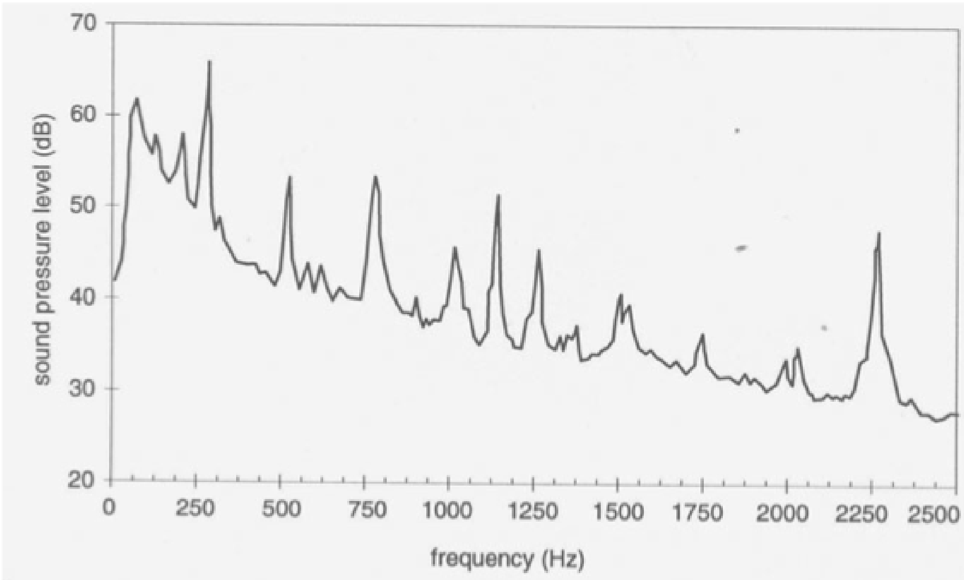


Figure 3: Typical sound pressure spectrum of machinery induced noise [12]

towards the rotor plane. As shown in figure 6 windspeed U_w causes a force F, which component makes the rotor turn. Similarly as with airplane wings, the relative flow creates high pressure on the upwind side (pressure side) and low pressure on the downwind side (suction side). [15]

The angle of attack α is defined as the angle between the effective flow direction and the airfoil chord line. The angle of attack can be increased by reducing the pitch angle (adjustable blade twist angle). A higher wind speed results in bigger vector length of U_w, thus also increasing the angle of attack. Normally a higher α generates a higher reaction force F and therefore a higher torque. [15]

A thin layer of air develops and partially sticks to the blade surface (figure 5). This is due to viscosity as the air flows past the blade surface. The layer is called the boundary layer and is usually less than a few centimetres thick. An increase in angle of attack usually results in a thicker boundary layer on the suction side and a thinner layer on the pressure side. At the blade surface the relative speed of air is zero, where as at the edge of the boundary layer the velocity is equal to U. Initially the boundary layer is laminar, but becomes turbulent closer to the end of the chord line. The laminar boundary layer is organized in layers, while the turbulent boundary layer is more chaotic by nature and contains vortices. [15]

2.4 Aerodynamic noise

There are three different source mechanisms, which could generate noise due to turbulent inflow (figure 5). This air flow can be caused by atmospheric boundary layer or by the wake from upwind turbines in a wind farm. Inflow turbulence noise is generated when the blade surface interacts with vortices in the air. The phenomena is dependent on prevalent atmospheric conditions, which varies with time and

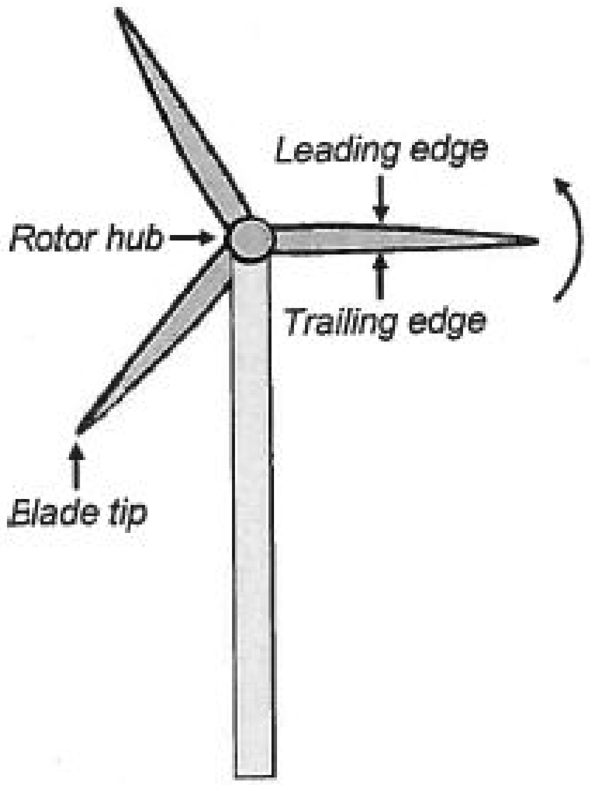


Figure 4: Wind turbine observed from downwind [15]

location. It is still unknown how much inflow turbulence noise contributes to the overall sound level. The pressure difference between the suction and pressure side compensates at the blade tip, thus creating a cross flow over the edge which creates a tip vortex [12]. Tip noise is caused by turbulent flow interaction with the tip surface. This source depends on the strength of the tip vortex and on the shape of the blade tip. Like the tip noise, also airfoil self noise can be generated in an undisturbed inflow. It is induced by turbulent flow over the trailing edge. [15]

Due to the strong dependence of generated sound power levels to the rotational speed of the blades, modern turbines generally rotate with variable speed. The control of the speed is done by pitch control rather than intentionally stalling the air flow over the blade, since stall creates a significant amount of noise. [16][17]

2.4.1 Low frequency noise

In addition to the blades also the presence of the tower causes changes in the incoming air flow. Cylindrical shape modifies the flow upstream and downstream of the tower. The flow cannot follow the round shape, which causes it to separate from the surface thus causing a wake. The generated turbulence and reduction in flow speed occurs on both sides of the tower, but is more evident downstream (figure 7). As a blade encounters the flow field, discrete frequency noise is generated. It is

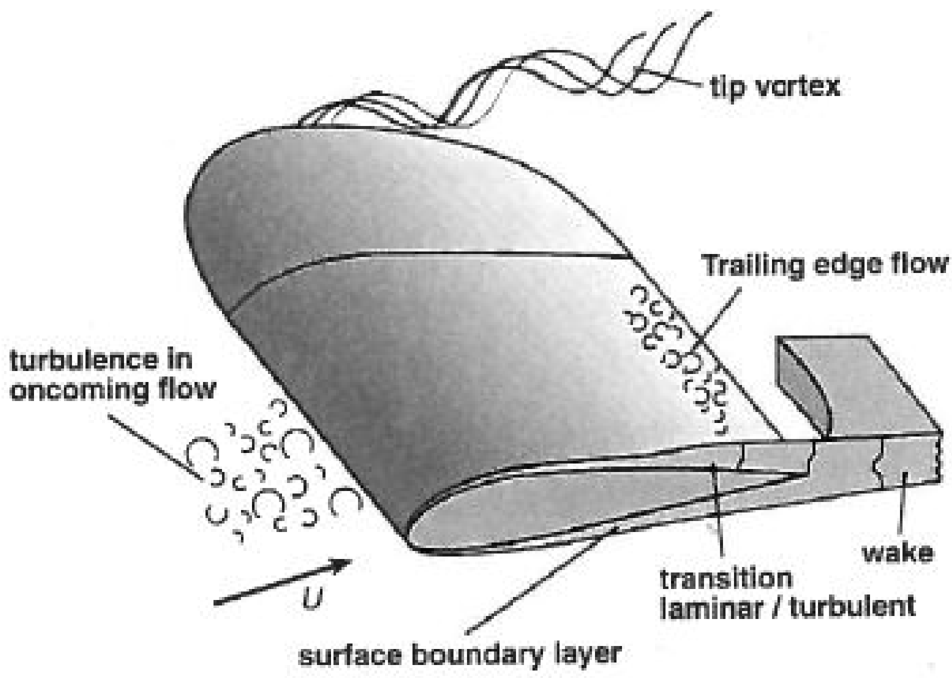


Figure 5: Air flow around the blade [15]

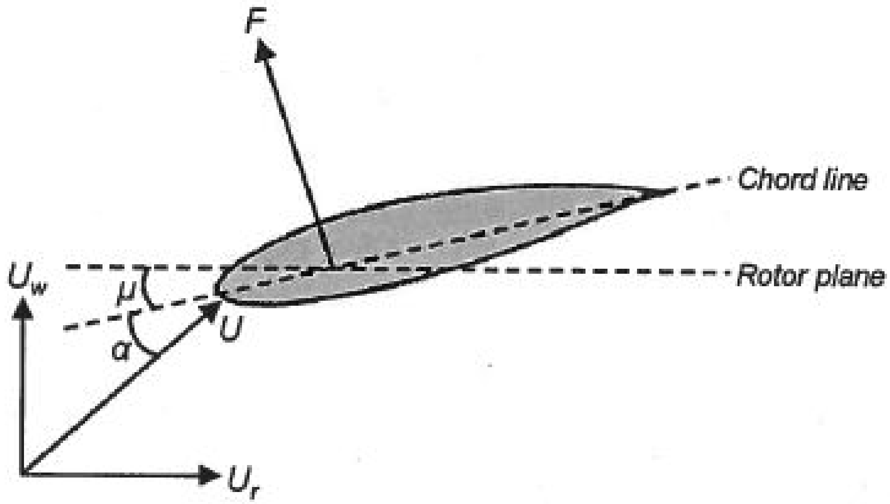


Figure 6: Airfoil with air flow angles [15]

generally of the order of 1-3 Hz and therefore does not have a substantial effect on A-weighted sound level. Though low-frequency noise can excite vibration of building structures especially when they are of light weight construction, such as wooden houses, located near to a wind turbine. Human organs have low eigen-frequencies and excitation could lead to annoyance. [12]

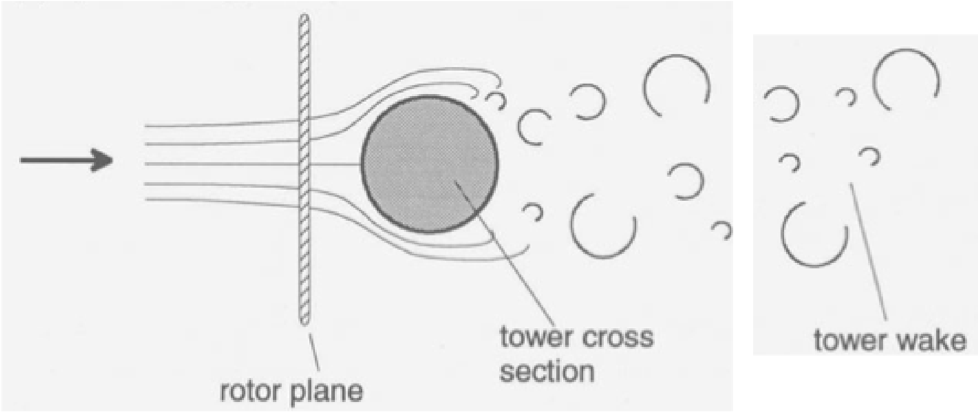


Figure 7: Tower induced air flow disturbance [12]

2.4.2 Inflow turbulence noise

A flow of air over a surface generates a boundary layer. Atmospheric boundary layer is developed by an air flow over the ground. The speed of the flow is altitude dependent, which is due to viscous friction of the air. This causes the velocity to be zero on the ground and gradually increase with height. [12] Atmospheric turbulence has two driving mechanisms: aerodynamic and thermal. Interaction between the flow and the surface generates turbulence. Longitudinal and vertical components are driven by different mechanisms. The main driver of the vertical component is wind shear in direction of the mean wind flow. The cause of the vertical component is both the shear and the thermal turbulence, which is caused by local buoyancy variations due to heating by the sun. The buoyancy effect is considerably less significant and can be neglected at wind speeds over 10 m/s. [12]

The size of the turbulent flow, also known as eddy is an important factor in determining whether the inflow-turbulence noise is high or low frequency. If the local flow velocity at the blade is U and if the length-scale of an eddy is Λ, the occured disturbance is at frequency $f = U/\Lambda$, which will be about the same as the radiated sound $f = c_0/\lambda$, where λ is wavelength. The noise will be low frequency, if the size of an eddy is much larger than the blade length (short side). Respectively, the noise is high frequency, if an eddy is of the same size or smaller than the blade dimensions. [12]

Causes of inflow turbulence noise are assumed to be the turbulent wake from upwind turbines. It generates broadband noise for frequencies up to 1000 Hz. Yet is uncertain how big is the contribution to the overall sound level. [15]

2.4.3 Airfoil self noise

Even in the unlikely case of turbulence free inflow, instabilities in the boundary layer on the turbine blade may occur. This phenomena in addition to eddies in the boundary layer interacting with the airfoil surface radiate noise. [12]

Trailing edge noise

An airfoil can radiate noise even in the case of turbulence-free inflow. Instabilities in the boundary layer can occur due to turbulent eddies. The laminar boundary layer on the airfoil surface transitions to turbulent at a certain chord line angle. The profile shape, the angle of attack, Reynolds number, the surface structure and inflow disturbances are the key factors in defining the occurence position.

At high Reynolds number turbulent boundary layers develop over the airfoil [18]. Turbulent eddies are weak sound sources at low Mach numbers, which is defined as $M = U/c_0$, where U is the free stream velocity and c_0 is the speed of sound. Eddies ability to produce sound is enhanced, if they are close to a sharp edge (figure 8). The interaction of eddies in the boundary layer with the blade edge increases its efficiency as a noise source. The angle between the eddy path and the trailing edge is predicted to be a factor in the magnitude of the induced noise [19]. [12]

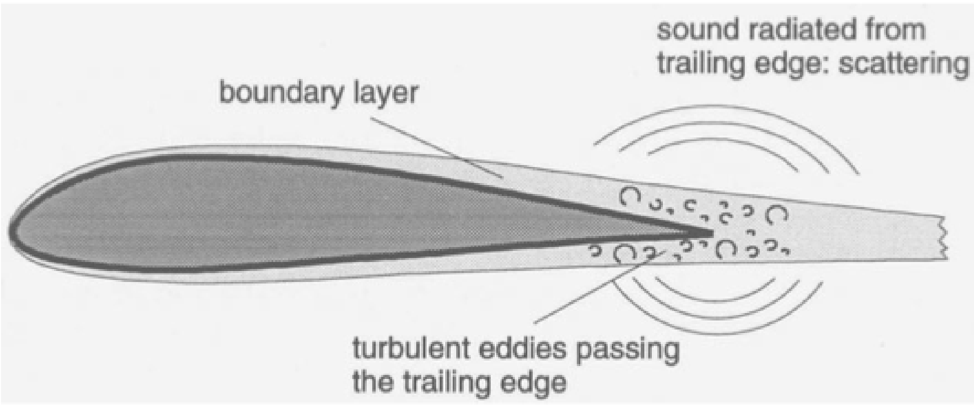


Figure 8: Generation of traling-edge noise [12]

Trailing edge noise is generally perceived as swishing sound, because of its broadband nature. The peak frequency is in the region of 500 – 1500 Hz depending on the characteristics of the turbine. The noise emitted from the trailing edge dominates in the high frequency region, if the flow is widely attached over the blade. [12]

Laminar-boundary-layer-vortex-shedding noise

Trailing edge thickness acts as a threshold for vortex shedding occurrence [15]. At low Reynolds number the laminar boundary layer may extend up to the trailing edge, whose instabilities can result in vortex-shedding noise. It is generated by a feedback loop between vortices being shed at the trailing edge and instabilities in the laminar boundary layer. The instabilities are amplified as a laminar vortex leaves the trailing edge thus creating pressure waves travelling upstream. When these instabilities reach the trailing edge, vortices with similar frequency characteristics are generated, forming a feedback loop. The created noise is tonal in nature. (figure 9). [12][18][20]

Most modern turbines are not expected to produce a significant amout of vortex shedding noise. It is assumed to be an issue only with small or medium-sized turbines. [12]

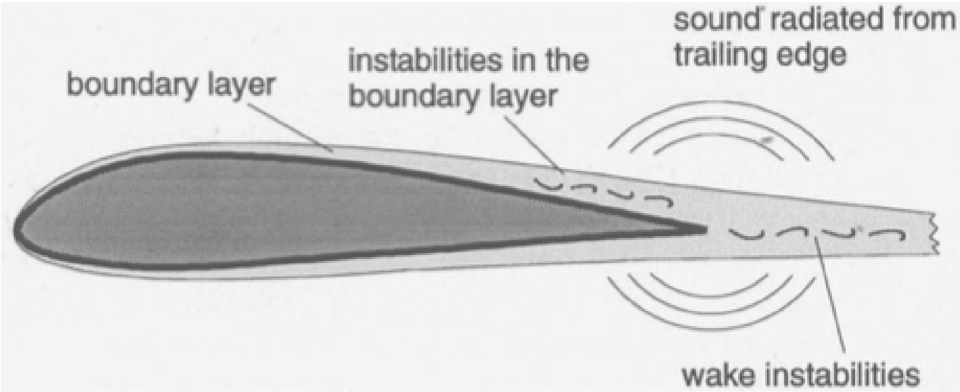


Figure 9: Generation of vortex-shedding noise [12]

Tip noise

Pressure differences between the suction and the pressure side create a cross flow over the tip thus creating a vortex (figure 10). The generated sound pressure is dependent on the air flow velocity over the edge. Therefore the vortex strength and the shape of the tip are important factors in the generation of the noise. Even though the tip vortex is considered to interact in similar way with the trailing edge as the boundary-layer turbulence does, the sound pressure level is typically smaller. [12][15][20]

It is commonly known that the tip vortex creates noise with broadband frequency content. Especially at higher frequencies the contribution can be significant. The order of the magnitude generated by the tip is still not agreed on. [12][20]

Trailing-edge bluntness noise

The threshold for blunt trailing edge noise to occur is the edge thickness h. When the critical thickness is reached alternating vortices produce surface pressure fluctuations in the near wake close to the trailing edge (figure 11), which results in tonal noise. The trailing edge thickness and shape are the main characteristics defining the noise frequency. Sharpening the edge shifts the peak of the created frequency towards the ultrasound region. Though there is a limit for the sharpness, which is stated by practise [12]. On the other hand when h increases the frequency and the bandwidth of the tone decrease. The generated noise is highly dependent on the flow speed that varies along the radius. Therefore blunt trailing edge noise might not result in a single tone but may also appear as a broadband increase in the spectrum. [15]

For trailing-edge noise the directivity and speed dependence of the blunt trailing-edge noise are considered equal. The geometry of the edge is a key factor in deter-

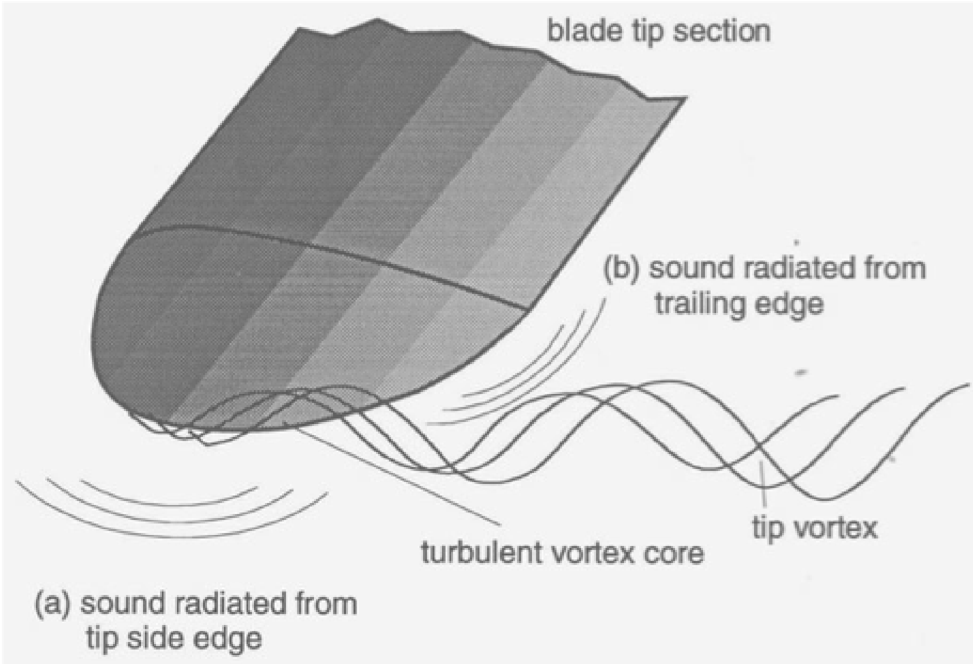


Figure 10: Generation of tip noise [12]

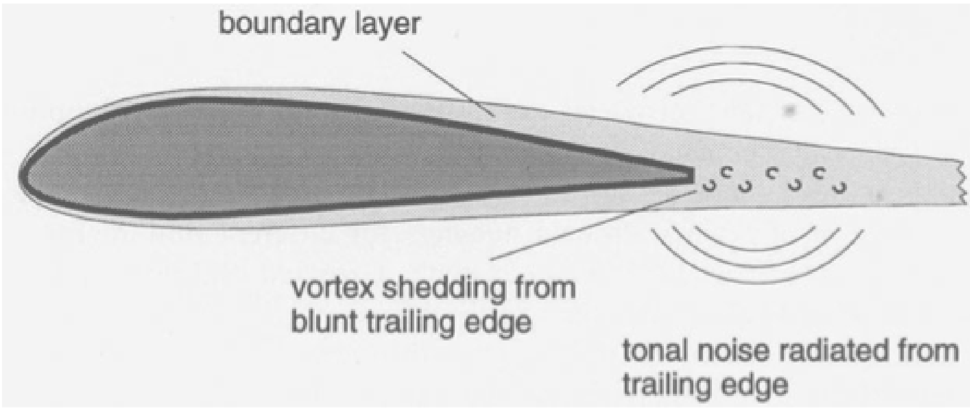


Figure 11: Generation of blunt trailing-edge noise [12]

mining the generated noise amplitude. Compared to a rectangular shape, a round or a 60-90 degree wedge may double or triple the amplitude. A wedge angle smaller than 45 degrees or a bevel angle less than 60 degrees can give much lower amplitudes. The relative amplitudes of different trailing-edge shapes are shown in figure 12. [15]

Stalled flow noise

When the angle of attack increases, at a certain point the size of the turbulent boundary layer on the suction side of the airfoil increases dramatically. This leads

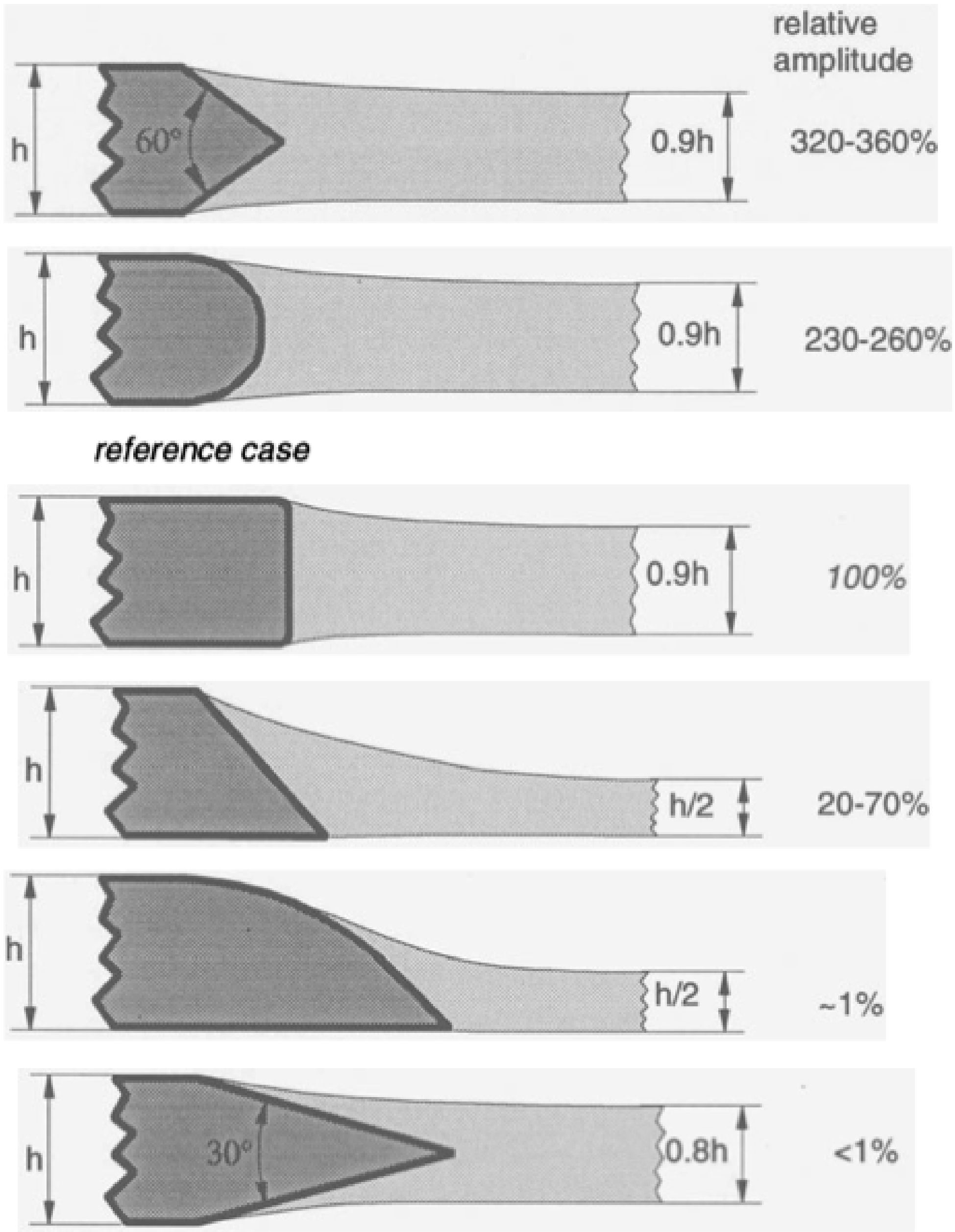


Figure 12: Relative amplitudes of different trailing-edge shapes [12]

to stall condition where the airflow is separeted from the surface (figure 13). Two types of separated flows have been identified. Mildly separated flow causes sound to radiate from the trailing edge and a deep stall causes noise to radiate from the unsteady flow over the entire chord of the airfoil. Over 10 dB increase is possible when comparing sound radiation due to stall conditions and low angles of attack. [12][20]

Most noise generated by stall is produced during the upper part of the rotor revolution. Sound is radiated both upwind and downwind direction. The sudden in-

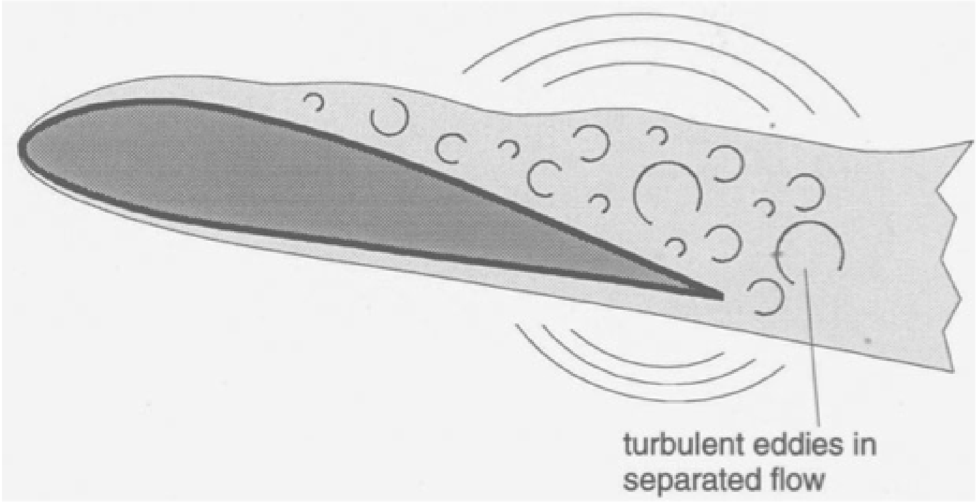


Figure 13: Generation of stalled flow noise [12]

crement in noise level causes significant amplitude modulation which is best detected at a longer distance from the source. [21]

Blade surface imperfection

In addition to the expected noise mechanisms also imperfections on the blade surface can cause noise. Generally every unwanted disturbance in the flow over the turbine blade can cause vortices, which lead to noise generation. Possible problems are among others damage or dirt due to environmental conditions. Also production process and natural wear are a possible cause. [12]

2.5 Rotating sound source

Turbine blade as a sound source is constantly moving with respect to the observer. The relative motion results in changes in the experienced noise amplitude and frequency, which is commonly known as the Doppler frequency shift. Given that a sound source is moving at speed U, the frequency f of the radiating sound is calculated as

$$f' = \frac{f}{1 - M\cos\theta}, \tag{1}$$

where $M = U/c$, c is the speed of sound and θ is the angle between the source velocity vector and the source-observer line at the emission moment. The percecived frequency increases when the source moves towards the observer and decreases if the source moves away. [15]

Also the amplitude is affected due the moving source, which is called the Doppler amplification. The magnitude of the amplification depends on the characteristics of the source. For aerodynamic noise sources with a low Mach number M, the perceived amplitude is changed by the factor

$$\frac{1}{(1 - M\cos\theta)^2}. \tag{2}$$

Similarly as the frequency shift, the amplitude is increased if the source moves towards the observer and vice versa. [15]

2.6 Directivity

It assumed that every aerodynamic source mechanism on the turbine blade is on the trailing edge except for turbulent inflow noise, which is assumed to originate from the leading edge of the airfoil. The trailing edge noise directivity pattern is frequency dependent. For low frequencies it is expressed as dipole while the high-frequency noise has a cardioid directivity pattern. [20][22]

For high frequency noise the airfoil can be considered a semi-infinite half plane. Most of the sound is radiated in the direction of the rotation, while only a little is radiated back. Thus practically all downward radiated sound is produced during the downward movement of the blades. The effect is uniform for all frequencies. [14][23]

Most significant sound sources are located at the outer part of the blade excluding the tip. The frequency peak source locations are determined as a function of frequency. It moves outward for increasing frequency. This is because of higher flow velocities and the smaller chord at higher radii, which results in a thinner trailing edge boundary layer. [14]

2.7 Sound propagation fundamentals

Not only the sound power level define the propagation distance of the noise emitted from a wind turbine. The atmospheric conditions and the location play a great role. The prevailing temperature profile, humidity, turbulence, wind speed and direction in addition to the terrain effect the spreading of the noise.

The propagation route and distance of the sound waves vary from day to day. The structure of the ground alters its sound reflecting characteristics due to the changes in weather (eg. rain). Even the speed of sound is dependent on the humidity and the temperature. Therefore for simplicity it is practical to review the environmental factors influencing sound propagation one by one assuming that others do not make their contribution.

2.7.1 Geometric attenuation

In a homogenous atmosphere without obstacles sound propagation is subject to geometric attenuation and atmospheric attenuation. The first is due to spreading of the sound energy, which can be considered as an expanding spherical surface. As the total area of the spherical wave front increases the sound intensity decreases at a rate inversely proportional to the distance r squared. The geometrical attenuation is independent of the frequency. Sound pressure level at a distance r_2 from the source relative to sound pressure level at a distance r_1 is calculated as

$$L_p(r_2) = L_p(r_1) + 20\log_{10}\left(\frac{r_1}{r_2}\right). \tag{3}$$

The sound pressure level L_p decreases by 6 dB when the distance from the source doubles. [24]

2.7.2 Atmospheric absorption

As the geometric attenuation also the atmospheric attenuation effects sound propagation in a homogenous atmosphere. There are two major mechanisms, which create losses to the propagating sound energy. First one is viscous losses, that is also referred to as classical absorption. Viscous losses are due acoustical energy being trasformed into heat by friction between air molecules. Classical absorption also includes diffusion losses and radiation losses, but they are not considered significant. [25][26]

The second absorption mechanism is relaxational processes. They cause the acoustic energy to be momentarily absorbed in the air-molecules, thus causing them to vibrate and rotate. The molecules are then able to re-radiate sound and partially disrupt the propagation of the incoming sound. [26]

Atmospheric absorption is frequency dependent and the absorption magnitude generally decreases with increasing humidity. Therefore dry air has the lowest ability to absorb sound energy. [26][27]

2.7.3 Ground absorption

Usually the arriving sound has more than one propagation paths. All the reflections are influenced by the ground surface, which generally cannot be considered as hard or perfectly reflecting. Typical surfaces absorb sound energy. Nevertheless the ground surface provides a path for transmission of acoustic energy especially for low incidence angles and low frequencies. [26]

Both the direct and reflected waves are subject to geometric and atmospheric attenuation effects. In addition there are three factors which define the difference between the waves at the receiver end. First, the reflected sound has travelled a slightly longer path. Second, by the impedance of the ground surface, the reflection modifies the amplitude and the phase of the wave. Third, the wavelength of the sound. Depending on their relative phases and amplitudes, the reflected and direct waves can interfere constructively or destructively. Constructive maximum being, when both waves arrive at the receiver having exactly the same phases and destructive maximum with opposite phases. The theoretical maximum for sound pressure level increment by reflection is 6 dB. [24][26]

2.7.4 Influence of wind and temperature

Wind is slowed down by friction as it flows over the ground, hence causing substantial vertical wind speed gradients. The wind velocity is lower closer to the ground. The speed profiles are dependent on the time, the weather and the nature of the surface. Also convection and the radiative temperature altering effects of the ground often result in vertical temperature gradients. [24]

Both wind and temperature gradients affect the speed of sound, the variations cause sound waves to refract. The direction is always in the direction from higher speeds to lower speeds of sound. Depending on the prevailing conditions, the curving trend is either upwards or downwards. [24]

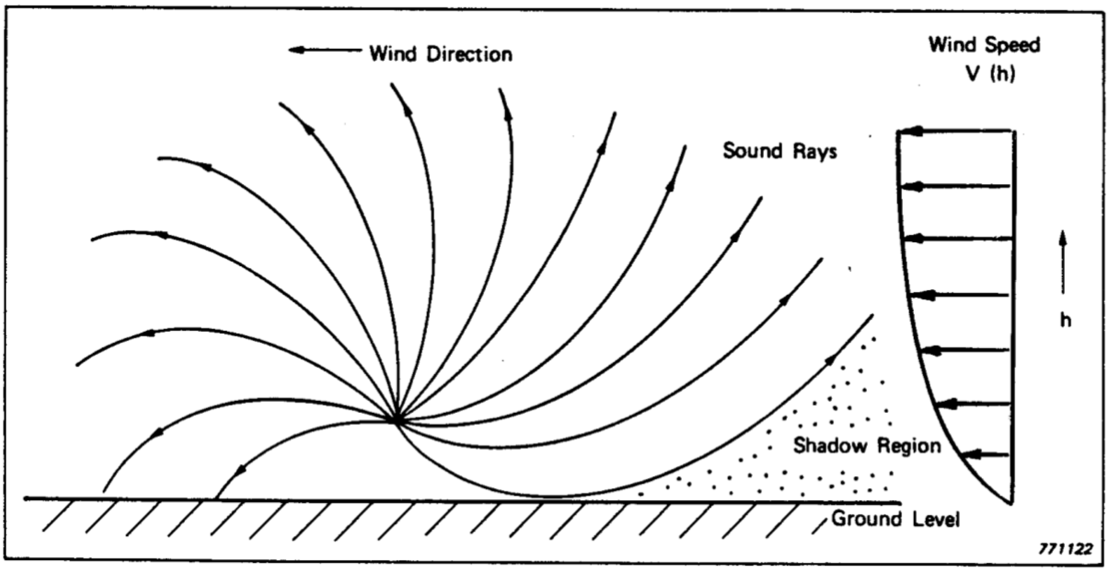


Figure 14: Refraction caused by wind [26]

Downward curving usually occurs under temperature inversion (air temperature increases with height), or when the wind blows away from the source. Respectively upward curving occurs for upwind propagation and opposite temperature gradient. Upward refraction also formes a shadow zone into which no direct sound is propagated. The typical wind speed profile's effect on refraction is shown in figure 14 and temperature profile's in figure 15. [24][26]

2.7.5 Turbulence

Turbulence is random fluctuations of airflow. It is caused by atmospheric instabilities of two kinds: shear and buoyancy. Shear instabilities are primarly generated by wind, but can also be caused by rough surfaces such as the ground and buildings. Buoyancy effects arise due to temperature differences between the ground and the air. Both mechanisms produce eddies, which introduce a local change in the speed of sound. Any change in the velocity of sound will result in local refraction. These local

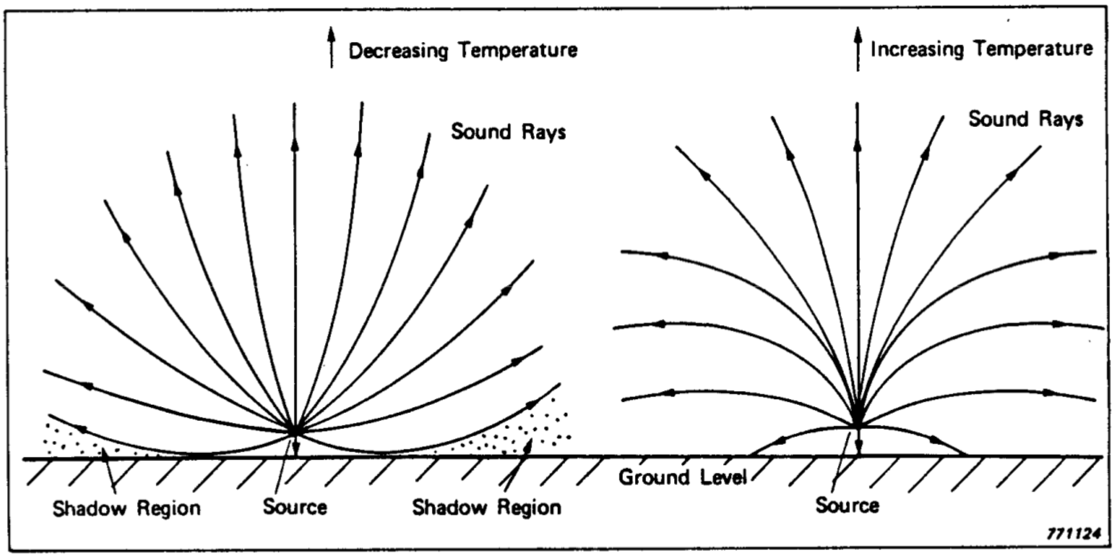


Figure 15: Refraction caused by temperature gradients [26]

changes are pretty random, thereby no systematic upwards or downwards changes in the propagation direction occur. [24][28][29]

The small local changes are also referred to as wave scattering. Due to the phenomena the energy of the wave is scattered about its mean direction of propagation. The extent to which any wave is scattered by turbulence depends on the wavelength and the size scale of the turbulence. [24]

The received magnitude of tonal noise is highly sensitive to the small variations of the propagation path length. Minor variations are important when considering constructive or destructive interference. The resultant effect of turbulence is that the level of tonal noise may vary significantly as turbulence causes the conditions for exact constructive interference to occur. Thus tonal noise is more variable than broad band noise over shorter time periods. [24]

2.7.6 Terrain

The terrain restricts reflection directions and if obstacles are high enough the line of sight. By interrupting the direct propagation path or by removing a ground reflected path, the received sound pressure level is reduced. The attenuation magnitude is subject to following factors: the distance from the source to the barrier; the distance from the barrier to the receiver; the heigths of the source, receiver and barrier. Also the frequency of the sound affects the propagation path. [24]

Sound waves diffract off obstacles, thereby being able to be detected behind them. The effect is frequency dependent. Low frequencies are re-emitted deeper into the shadow region (figure 16). Therefore barriers attenuate sound better with increasing frequency. Though because of the high height of wind turbines the terrain affects rather the reflections from the ground than the direct path from the source to the receiver. [24]

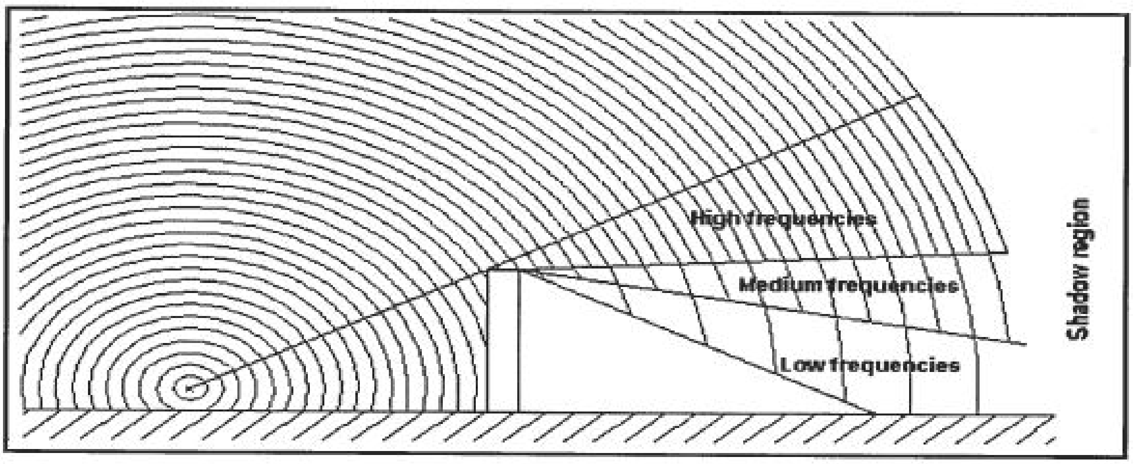


Figure 16: Frequency dependence of diffraction over an obstacle [24]

3 Signal analysis methods

When the goal is to extract details from a continuous signal, it needs to be processed first. Since noise emitted from a wind turbine keeps constantly changing with time, only short samples of a recording can be analysed at a time.

In this section the most important signal analysis methods, for determination of frequency content of a noise recording, are explained. The calculation guideline of tonal audibility analysis requires the use of reviewed techniques.

3.1 Sound pressure calculations

Sound needs a medium to travel. The waves travel in solid, liquid or gas. In this work only air-borne sound is considered. In air sound waves are longitudinal changes of air pressure, small fluctuations of pressure around the prevalent sound pressure. [30]

Our ears can detect extremely small periodic variations in air pressure. The minimum variation in pressure which the ear can respond is about 20 μPa at 1000 Hz. This threshold of audibility varies from person to person and is frequency dependent. The pressure is less than one billionth of atmospheric pressure.

In order to understand the relativity of pressure changes better sound pressure level (L_p) is used. It is basically calculated by comparing the measured sound pressure p to the reference pressure $p_0 = 20\mu Pa$ and transformed into logarithmic form

$$L_p = 20\log_{10}\frac{p}{p_0}. \tag{4}$$

Sound pressures can be summed together and changed to sound pressure level with equation

$$L_{\sum} = 10\log_{10}\left(\frac{p_1^2 + p_2^2 + p_3^2 + ... + p_n^2}{p_0^2}\right), \tag{5}$$

which can be simplified to

$$L_{\sum} = 10\log_{10}\left(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} + 10^{\frac{L_3}{10}} + ... + 10^{\frac{L_n}{10}}\right). \tag{6}$$

Average sound pressure level, which is later in this work also referred to as energy average, is calculated in a similar way

$$L_{average} = 10\log_{10}\left(\frac{1}{n}\left(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} + 10^{\frac{L_3}{10}} + ... + 10^{\frac{L_n}{10}}\right)\right). \tag{7}$$

When an energy sum has to be divided, it is done by dividing the energy sum before applying the 10-based logarithm.

3.2 Signal processing

Real life signals are continuous by nature. A computer cannot analyze analog signals, so they have to be transformed into digital form. Computer based calculations are done sample by sample in discrete form.

3.2.1 Discrete Fourier transform

A waveform can be represented as a sum of pure tones. In order to resolve which frequencies are included in a time-domain signal a transform to the frequency domain has to be done. In the field of digital signal processing discrete Fourier transform (DFT) is one of the most powerful tools. With DFT it is possible to analyze and manipulate discrete time signals.

DFT is used to determine the frequency content of a discrete signal sequence, which is a set of values gathered by periodical sampling of an analog signal in the time domain. The base for DFT is continuous Fourier transform, which is defined as

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}dt, \tag{8}$$

where $x(t)$ is a continuous time-domain signal, t is time and j is the imaginary unit. [31]

Mathematically machine computation restricts the Fourier transform in two ways. The calculation is only possible if the signal has a finite duration. Also the variables of time and frequency can only have discrete values. Discrete Fourier transform of length N is defined as

$$X[k] = \sum_{n=0}^{N-1} x[n]e^{-j2\pi kn/N}, \quad 0 \leq k \leq N-1, \tag{9}$$

where $x[n]$ is the time-domain sequence. [32]

DFT has been recognized to be computationally heavy. Therefore a lighter algorithm called fast Fourier transform (FFT) was developed. Most computer based calculations are done by using FFT.

3.2.2 Spectral leakage

The DFT of real life sampled signals gives only an approximation of the true spectra. A characteristic called spectral leakage causes the calculated spectra to show values that are not correct. [31]

As said in the previous section, DFT is restrained to work only on a finite sequence of N input values to produce an N-point transform. The transform's analysis frequencies (f_a) can be calculated with equation

$$f_a(m) = \frac{mf_s}{N}, \quad 0 \leq m \leq N-1, \tag{10}$$

where f_s is the sampling frequency. The fundamental frequency f_s/N is also called frequency resolution.[31]

The DFT produces correct results only if the analysed signal contains frequencies exactly at multiples of the fundamental analysis frequency (equation 10). All the other frequency components will influence the results of all the other output analysis frequencies. This is called leakage. [31]

In figure 17a is illustrated an example, when in frequency-domain a signal's sampled values are exactly at a DFT bin center. Squares in the figure illustrate bin centers acquired with equation 10. Results of this is that there is only one nonzero value. In real life most cases end up having values outisde the bin center (figure 17b), which causes leakage.

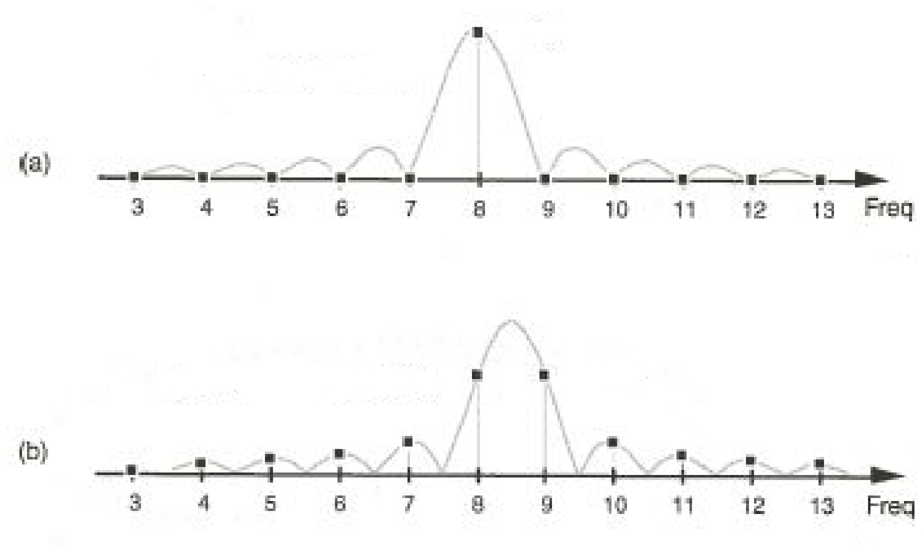


Figure 17: (a) DFT frequency response with sampled values at bin center (b) DFT response with sampled values outside bin center [31]

The problem arises when frequency bins close to each other contain values of different magnitude. Bins containing low amplitude signals can be corrupted by neighboring high amplitude signal's sidelobe levels. [31]

Spectral leakage is not possible to avoid. The best solution to the problem is to try to minimize it. A technique called windowing is a common method to reduce the effects. [31]

3.2.3 Windowing

Window functions are used to limit the signal in time domain. In addition by choosing a suitable window the accuracy of DFT analysis can be improved. [31]

DFT requires the processed signal to have finite length. The simplest way of time-limiting is by multiplying the original signal by rectangular window function (figure 18)

$$\omega_r[n] = \begin{cases} 1, & \text{for } n = 0, ..., N-1 \\ 0, & \text{otherwise.} \end{cases} \tag{11}$$

The operation sets limitations to the signal in the time-domain and its values are zero outside the boundaries.[33]

As mentioned in section 3.2.2 leakage is caused by frequencies that are of length that does not fit exactly to the DFT sequence. Therefore rectangular window is not optimal for reducing spectral leakage, because at the beginning and in the end the amplitude values are higher than zero. [31]

The strong discontinuities at the frame borders of the rectangular window are likely to cause aliasing problems. In order to reduce aliasing and spectral leakage, a window function is needed. It has to smoothly reduce in time-domain towards the edges so that there is no sharp discontinuity. Hanning window (figure 18) is an example of such a window:

$$\omega_h[n] = \begin{cases} 0,5 - 0,5\cos(\frac{2\pi n}{N-1}), \ for\ n = 0, ..., N-1 \\ 0,\ \text{otherwise.} \end{cases} \tag{12}$$

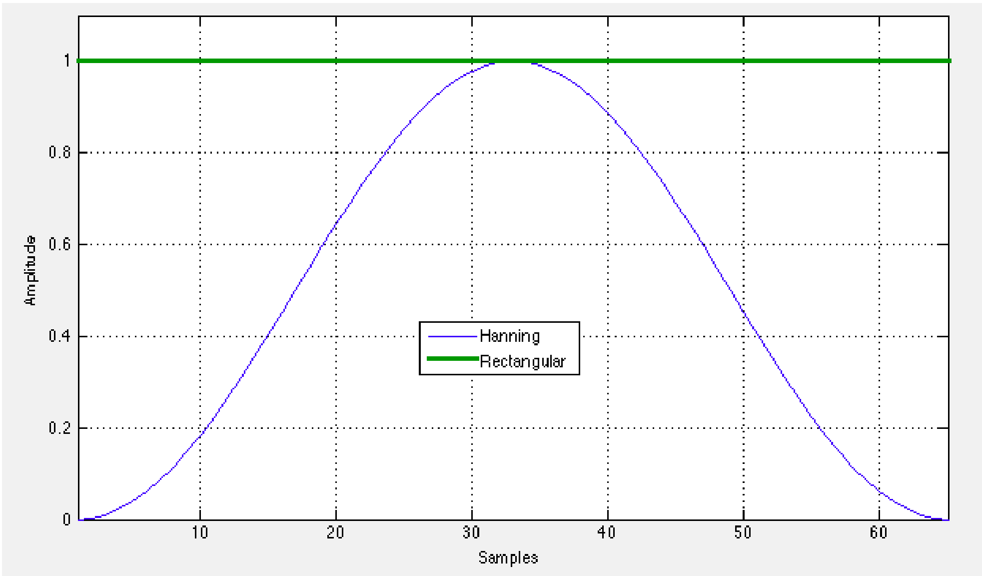


Figure 18: Rectangular and Hanning windows in time domain

Spectral leakage is greatly affected by the sidelobes of the Fourier transform of the window function. In general the longer the length of the window, the narrower the main lobe will be. [33]

In figure 19 rectangular and Hanning windows' magnitude responses in frequency domain are compared. The cause of the strong sidelobes of the rectangular window are the sudden changes between one and zero. Whereas Hanning window's smooth transitions reduce the sidelobes significantly. Smaller sidelobes are a trade-off for wider main lobe and lower frequency resolution. Though, smaller leakage to other frequency bins outweights the loss of frequency resolution. The most important factors in window selection are the main lobe widening, first sidelobe levels and how fast the sidelobes decrease with increasing frequency. [31]

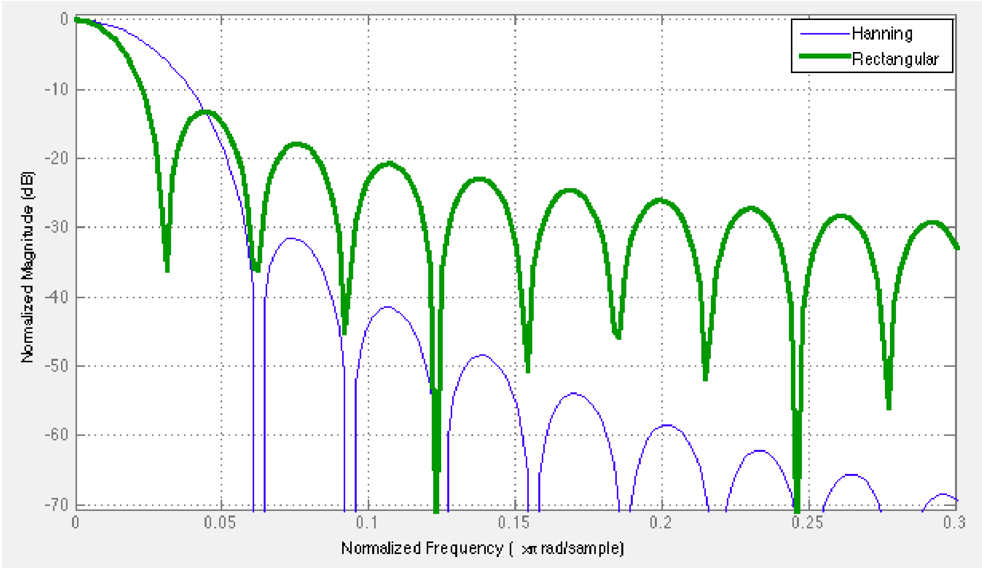


Figure 19: Rectangular and Hanning window magnitude response

3.2.4 Overlapping windows

Window functions tend to reduce the amplitude near the edges in the calculation of the frequency spectrum. Attenuation causes signal data to be lost. In order to minimize the lost data, windows overlapping in time can be used in processing the signal. The general idea is that a window recovers a portion of the previous frame that otherwise would be lost. This processing method also reduces the total measuring time needed. A spectrum can be calculated using the data that would be lost without the overlap, thus reducing measurement time needed to process certain amount of spectra.[34]

In figure 20b the effect of a single Hanning-window is demonstrated on a signal (figure 20a). It is clearly visible that the window limits the signal in time and attenuates the edges.

The maximum overlap is 50% when considering a simple way of processing. Then only two windows cover each other. In figure 20c is shown the summation of the amplitudes of three consecutive windows. They sum up to a constant outside half a window length from the beginning and the end.

3.3 Frequency bands

The most common way to present frequency based information of air-borne sound is to use frequency bands. International Organization for Standardization (ISO) has agreed on preferred frequency bands for noise measurement and analysis (ISO 226). [35]

3.3.1 Octave bands

The widest standardised band is the octave band. Octave is a band where the upper frequency limit (f_u) is double compared to the lower (f_l). The bands are named after their centre frequency. It is calculated for band m as

$$f_m = \sqrt{f_l\ f_u} = \sqrt{2} f_l. \tag{13}$$

The centre frequency of band $m+1$ is calculated as

$$f_{m+1} = 2\ f_m, \tag{14}$$

and the bandwidth as

$$\Delta f = f_u - f_l = f_l, \tag{15}$$

The preferred bands' centre frequencies are listed in ISO 226 standard. [36]

3.3.2 Third octave bands

An octave band can be a little inaccurate, if it is desired to survey more specific frequency information. This is achieved by reviewing noise with narrower bands. Another standardised option is the third octave band. The centre frequencies of the third octave bands do not follow an exact octave sequence. They are adjusted slightly so that their centre frequencies are one-tenth decade numbers. For example 35 Hz and 40 Hz have the logarithms 1.5 and 1.6. Band numbers are formed accordingly, in this case they are 15 and 16. [35] Limits for a band are defined as

$$f_u = 2^{1/3}\ f_l, \tag{16}$$

bandwidth as

$$\Delta f = f_u - f_l = f_l(2^{1/3} - 1), \tag{17}$$

centre frequency of a band as

$$f_m = \sqrt{f_l\ f_m} \tag{18}$$

and the centre frequency of the next band as

$$f_{m+1} = 2^{1/3}\ f_m.\ [36] \tag{19}$$

Calculation of the third octave bandwidth for any center frequency f_c is done by equation

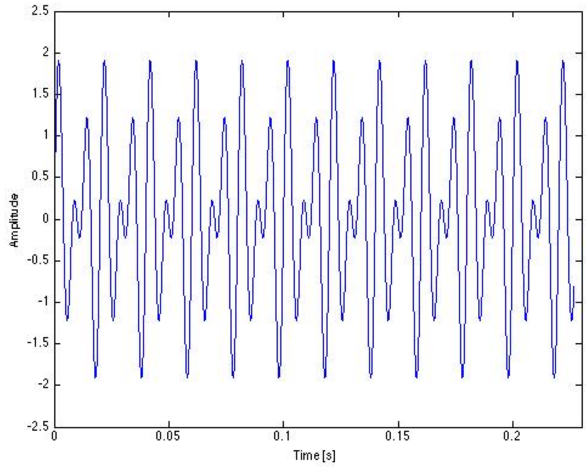
$$\Delta f = f_c \frac{2^{1/3} - 1}{2^{1/6}}\ [37]. \tag{20}$$

3.3.3 Narrow band

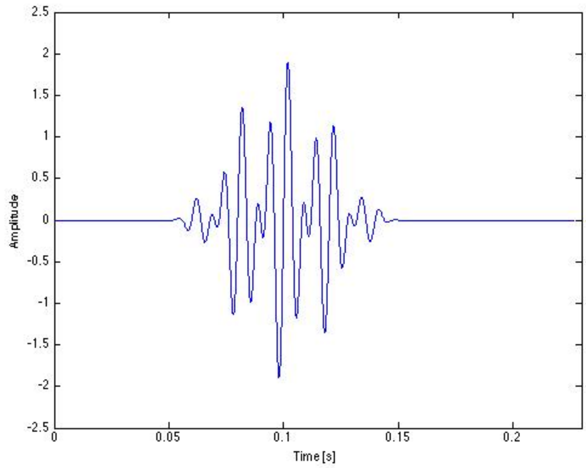
Although usually very narrow bands are not considered as a very practical way of presenting noise measuremement data, the analysis method used in this work requires calculations on spectra with frequency resolution of 1-2 Hz.

3.4 Wind speed bins

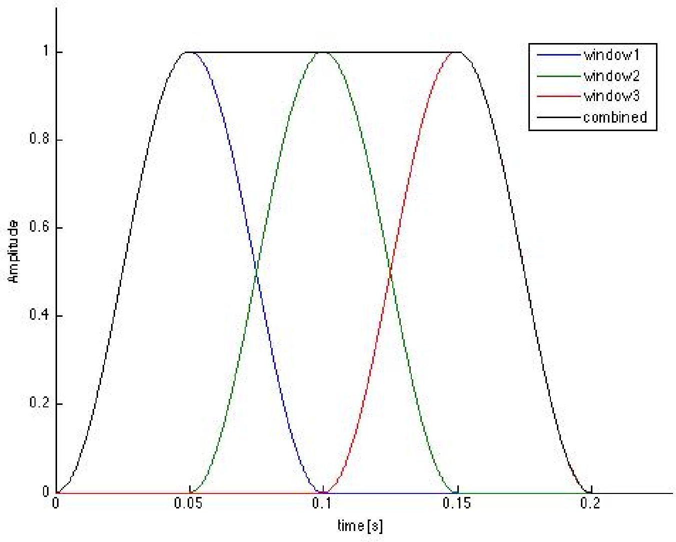
Due to characteristics of wind it is not very practical to use exact wind speed as a categorizing factor. Thus wind speed bins or intervals are used. IEC 61400-11 defines a bin to be 0.5 m/s wide and centered around integer and half-integer wind speeds [38].



(a) Pure signal



(b) Hanning windowed signal.



(c) Overlapping Hanning windows.

Figure 20: Details of windowing

4 Tonality

Auditory perceptions are dependent on an individual. General rules have been created by doing listening tests for determination of tonal audibility. Among others psycho-acoustical phenomena tonality is a cause of annoyance. Magnitude and frequency are the most important characteristics in analysis of narrow band noise.

Tones may exist in noise even though they cannot be heard. By a theorem, masking is only effective within a certain bandwidth around a tone. In this section key features of determination of audibilty are presented.

4.1 Hearing threshold

In sound pressure level calculations it is assumed that relative to 2x$10^{-5}Pa$, 0 dB is the lowest audible sound pressure level. Even so, the threshold of hearing is frequency dependent ranging over 20 Hz to 20 kHz. Our hearing system is the most sensitive to tones around 4 kHz.

The threshold in quiet basically means the lowest sound pressure level for pure tone that is just audible to an average human. The just-noticeable level is frequency dependent.

The threshold increases towards the low frequencies as it does for very high frequencies. The most uniform region of hearing threshold situates between 500 Hz and 2 kHz just below the most sensitive band of 3.5-4 kHz. At this sensitive bandwidth almost every person with normal hearing can detect sounds below 0 dB. Even though the frequency range is assumed to be between 20-20000 Hz, the far ends are unlikely to be detected. This can be seen in figure 21, the curve for threshold in quiet indicates a radical rise in threshold at 16 to 18 kHz [39]

Individual differences can usually be seen especially towards low and higher frequencies. However our hearing system is most easily damaged in the frequency range between 3 and 8 kHz, if it is exposed to high sound pressure levels. Age is also a factor in shift of hearing sensitivity particularly at high frequencies. In figure 21 the threshold in quiet is presented for different age groups. For frequencies below 2 kHz, the hearing sensitivity remains almost the same. [39]

4.2 Loudness

The auditory sensation of hearing different sound levels of various frequencies is not easily comparable with sound pressure level values. Higher sound level does not necessary sound louder, because the sensitivity of the ear is frequency dependent. [30]

Loudness is defined as the magnitude of an auditory sensation. The magnitude of a sound is expressed as by the magnitude of the standard reference tone at 1 kHz, which to an average person sounds equally loud. The unit for expressing differences in loudness levels is called phon. Two sine waves with equal level in phones sound equally loud. [40][41]

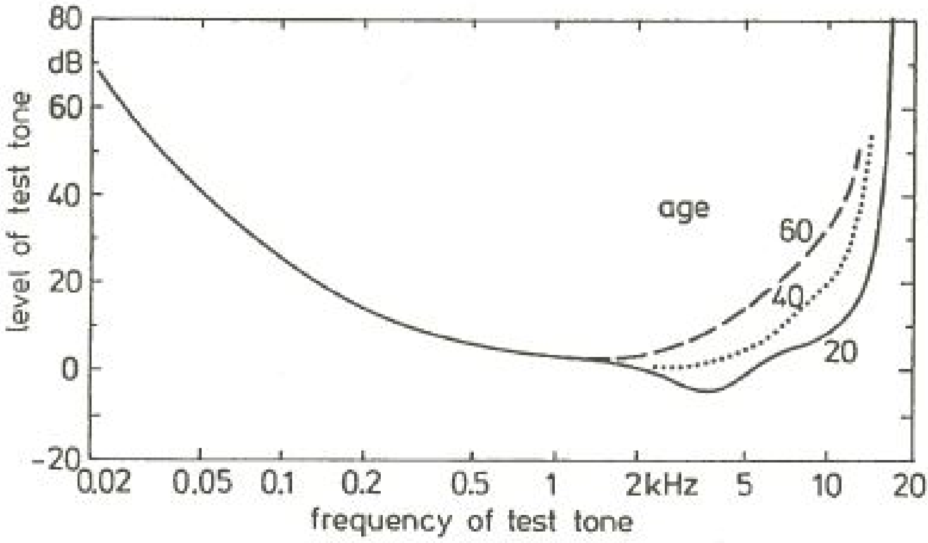


Figure 21: Hearing threshold in quiet [39].

Equal loudness contours describe the sensitivity of the hearing sensitivity throughout the audible frequency range. The contours are labeled in phones. Each curve demonstrates the sound pressure levels at different frequencies, which sound equally as loud as the sound pressure level at 1kHz. Hearing sensitivity reaches its maximum between 3.5-4 kHz. The curves recommended by the ISO 226 standard are presented in figure 22. [30]

4.3 A-weighting

For measuring overall sound level the equal loudness contours are not a convenient tool. The contours are defined for single tones or limited complexity of sound. Frequency weightings were developed to provide a base for noise assessments where it was desired to measure noise impact on people. The unit of A-weighted sound pressure level dBA has established itself as the most common indicator in researches considering noise.

Frequency weighting curve A is recognized to be the inverse of the 40-phon Fletcher-Munson equal loudness contour. Inversion of the curve is done to make it indicate gain instead of level. The definition of the A-weighting curve is in the standard for sound level meters IEC 61672. The magnitude response is presented in figure 23. [42]

A-weighting curve is used as a correction for measured values. Hence it is used for correcting measurement results into describing the auditory sensation. The values are added to every frequency. In IEC 61672 the weighting values are presented with tolerance limits in third octave bands from 10 Hz to 20 kHz. The corresponding

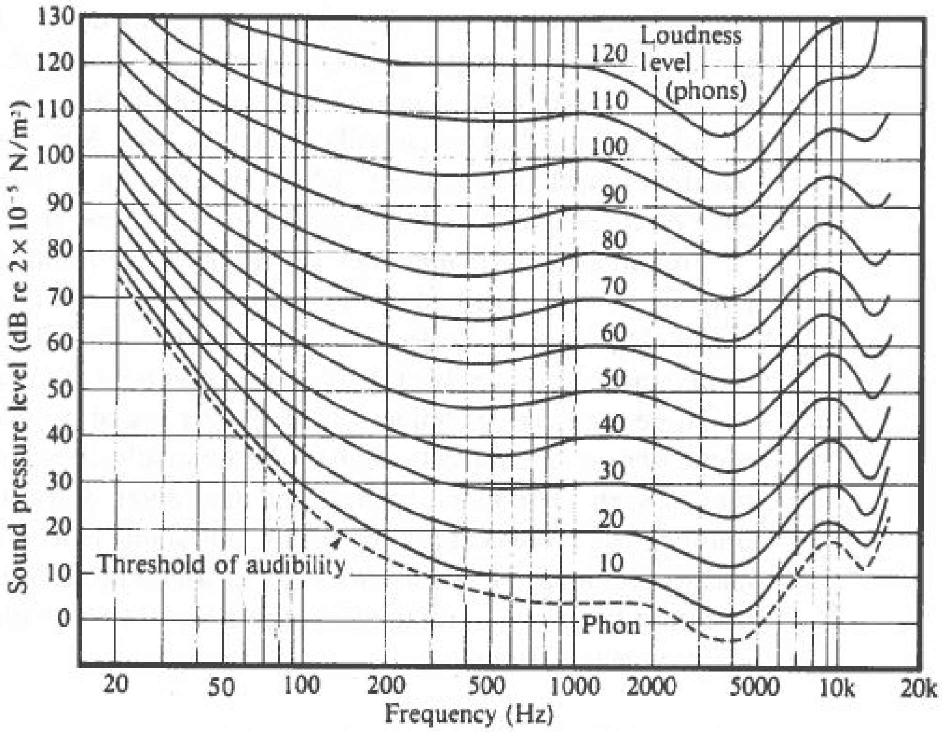


Figure 22: Equal loudness contours [30].

weighting function is given by the standard as

$$A(f) = 20\log_{10}\left[\frac{f_4^2 f^4}{(f^2+f_1^2)(f^2+f_2^2)^{\frac{1}{2}}(f^2+f_3^2)^{\frac{1}{2}}(f^2+f_4^2)}\right], \tag{21}$$

where approximated values for $f_1 - f_4$ are $f_1 = 20.60\text{Hz}$, $f_2 = 107.7\text{Hz}$, $f_3 = 737.9\text{Hz}$ and $f_4 = 12194\text{Hz}$. [43]

4.4 Concept of masking within the critical band

Tones can be masked by noise emitted from a particular source or from the background. There are two possibilities for a tone to become audible in a noisy environment. The first is to wait until the background noise level has decreased and the second is to increase the loudness of the tone. In addition to total masking also partial masking possible. It occurs when masking signal increases and causes a reduction in the loudness of the tone. [39]

Due to frequency selectivity of the auditory system it is possible to detect two separate tones simultaneously. Though, if the tone frequencies are close to each other the other tone could become inaudible. This is called masking. [44]

Fletcher assumed in his work, that only a part of the noise spectrum plays an important role in masking a tone. The most effective bandwidth lies close to the tone frequency, within the critical band. [39]

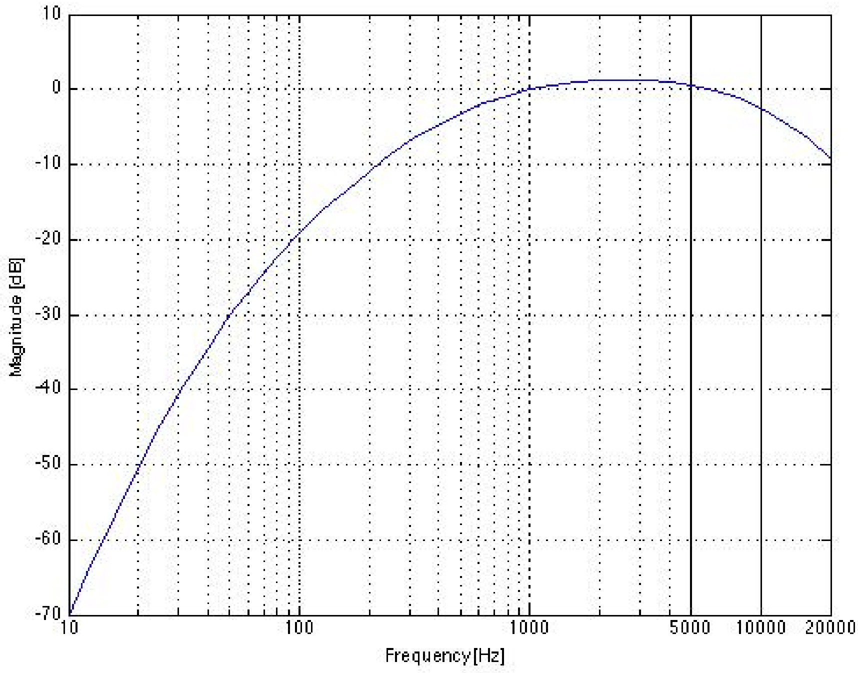


Figure 23: A-weighting curve

Critical band is derived from the behavior of amplitude envelopes of tones on the basilar membrane. If the envelopes of two pure tones have significant overlap, they are considered to lie within the same critical band. [30]

As seen in figure 24 the critical band Bc is constant at low frequencies but increases logarithmically towards higher frequencies. It is defined as

$$Bc = 25 + 75\left(1 + 1.4\left[\frac{f_c}{1000}\right]^2\right)^{0.69}, \tag{22}$$

where f_c is the center frequency of the band. The formula is an approximation of the original table based values by Zwicker [45] with an accuracy of $\pm10\%$. [46]

Bandwidth of the critical band is considered as narrow. When narrow-band noise is used for masking a tone, the masking threshold lies lower than the actual noise level. E.g. 60 dB noise with critical bandwidth around 1 kHz tone, the maximum of the masked threshold is 3 dB lower. Another characteristic for narrow-band masker is that the frequency dependence of the masked threshold is broader for lower frequencies. When observing the shape of the masking threshold around the center frequency, it can be seen that before the center frequency f_c the threshold line show a very steep increase and after a flatter decrease. Thus, the masking effect spreads out further towards the higher frequencies. The two characteristics are demonstrated in figure 25. [39]

When the bandwidth of the masking noise exceeds the critical bandwidth, the magnitude of the just masked threshold for a tone in the center of the band does

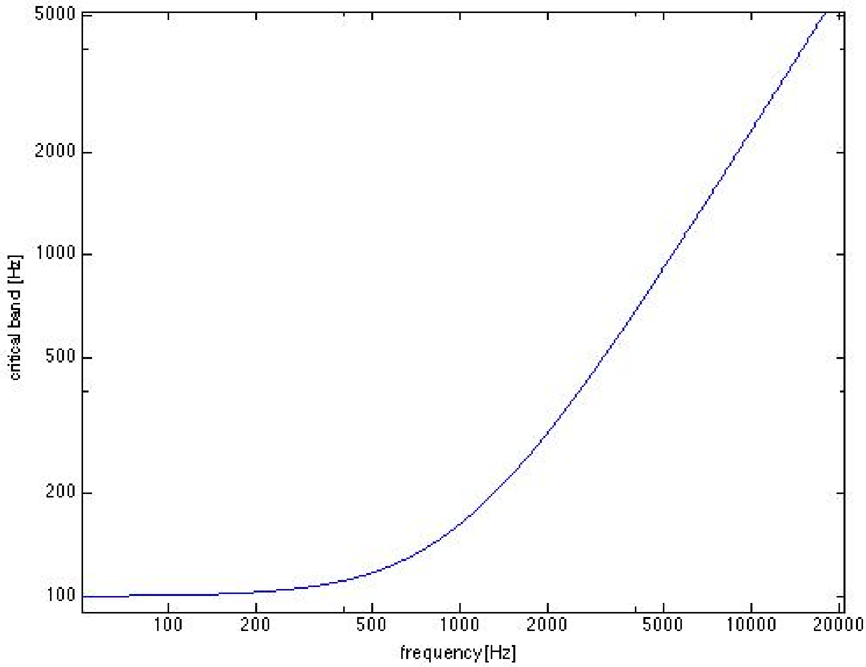


Figure 24: The frequency dependency of the width of the critical band.

not increase. The masking effect expands into a trapezoidal form without increase in height. [47]

Perceived loudness of tones is significantly influeced by their frequency separation. When the frequency difference exceeds the critical bandwidth, the total loudness begins to increase. Thus broadband sound such as noise seems louder than pure tones having the same sound pressure level. [30]

4.5 Determination of tonal audibility

Tonal audibility is defined by comparing the difference between the tone level L_{pt} and the noise level L_{pn}

$$\Delta L_{tn} = L_{pt} - L_{pn} \tag{23}$$

to a criterion curve, which is calculated as

$$\Delta L_{tn,crit} = -4.5 - \log_{10}\left[1 + \left(\frac{f}{502}\right)^{2.5}\right], \tag{24}$$

and shown in figure 26. If ΔL_{tn} is below the masking threshold curve, the tone is considered masked and non-audible for average listeners. Levels above the criterion curve are considered prominent and clearly audible. [48]

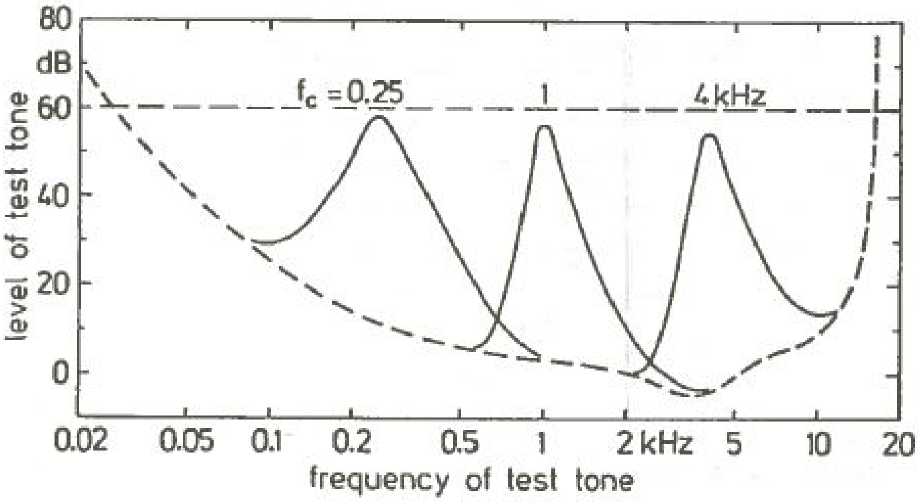


Figure 25: Level of a tone just masked by critical-band wide noise with level of 60 dB [39].

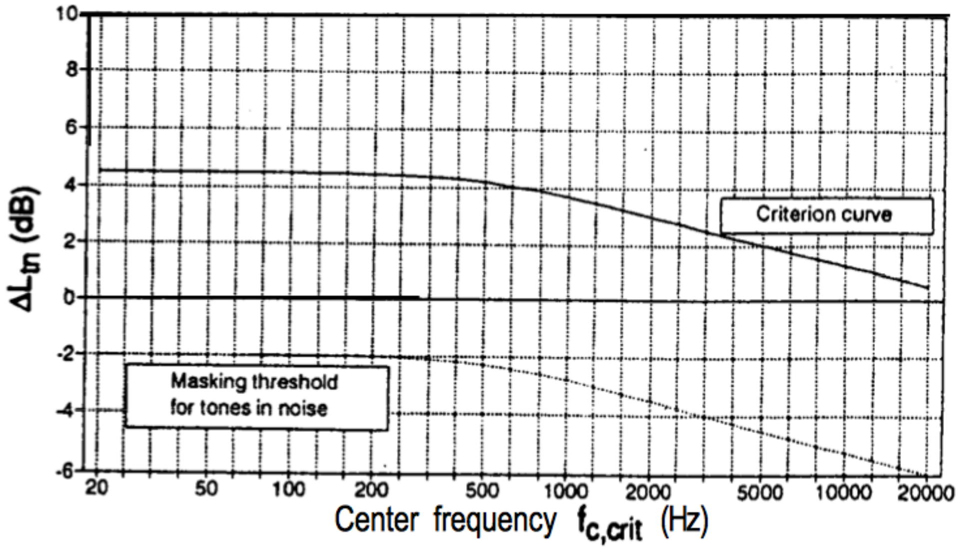


Figure 26: Criterion curves for tonal audibility [48].

4.6 Just-noticeable changes in frequency

The ability to distinguish the difference between two nearly equal tones is called just-noticeable difference (jnd). If two stimuli differ less than the jnd, the divergence cannot be heard. [30]

Two approaches for changes in frequency are presented in this section, threshold for frequency variation and just-noticeable frequency differences. By variation it is meant that the studied tone is modulated in frequency.

4.6.1 Threshold for frequency variation

Fast change in frequency causes a click sound. Therefore just-noticeable variations in frequency (jnvf) are measured using frequency modulation. To describe the deviation Δf is used. It defines the maximum change in frequency from the tone f in one direction. The frequency changes between $f - \Delta f$ and $f + \Delta f$, which makes the total variation in frequency $2\Delta f$. [39]

The auditory system is most sensitive for frequency variations at frequency modulations of about 4 Hz. In figure 27, it is shown how the jnvf varies in frequency for frequency-modulated tones of loudness 60 phon with 4 Hz modulation frequency. At low frequencies the threshold of jnvf is approximately constant, but above 500 Hz it increases nearly in proportion to frequency. [39]

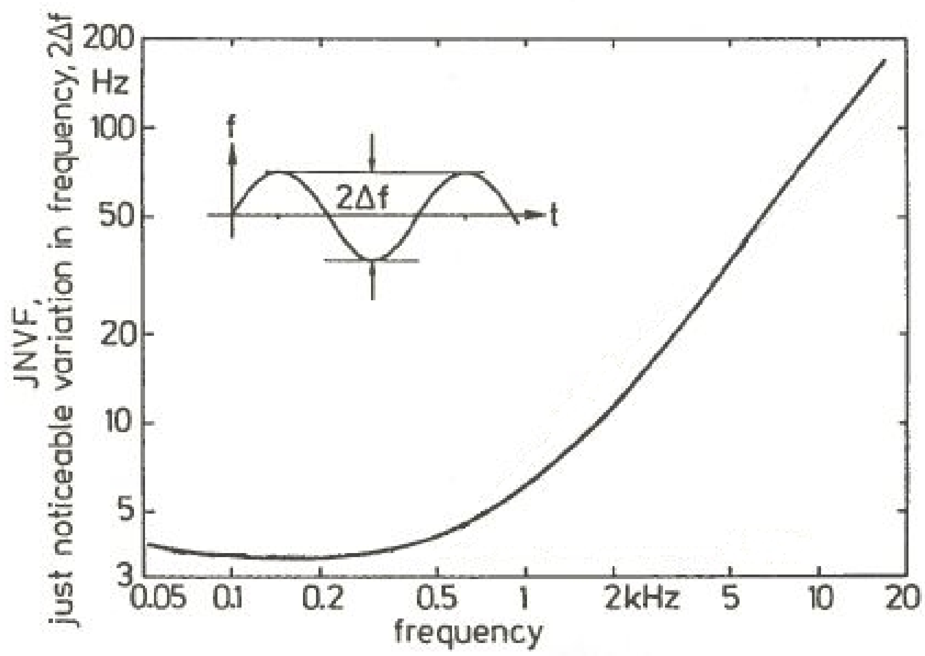


Figure 27: Just-noticeable frequency variation at a modulation frequency of 4 Hz. [39]

The frequency of modulation plays an important role in the jnvf value. This frequency dependence is presented in figure 28. The figure shows again that our auditory system detects best modulation frequencies around 4 Hz.

The $2\Delta f$ increases rapidly between frequencies 10 and 50 Hz. This ascent ends earlier for low carrier frequencies than for higher carrier frequencies. For 8 kHz the ascent continues up to modulation frequencies of 300 Hz. The curve presented in figure 28 is for a carrier frequency of 1 kHz and the rising slope ends at about 70 Hz. This difference in behavior between the various carrier frequencies is caused by the selectivity of our hearing system. At very low modulation frequencies the increment of jnvf seems to be produced by a limited memory. Our ability to remember the

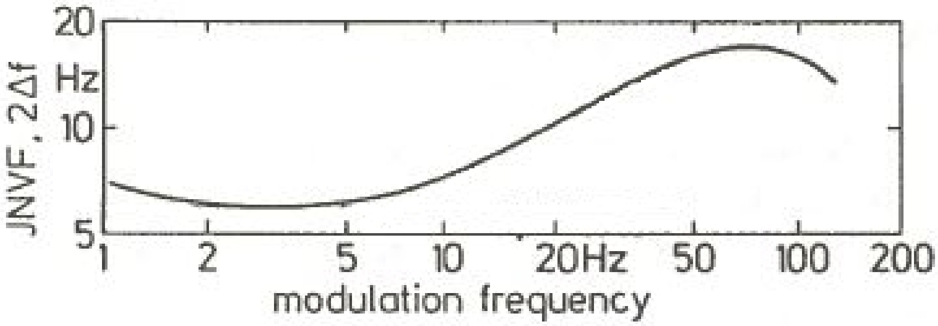


Figure 28: Just-noticeable frequency modulation as a function of modulation frequency (center frequency 1 kHz).[39]

pitch of a tone after a while is poor. Hence, the value of $2\Delta f$ rises towards very low modulation frequencies. [39]

4.6.2 Just-noticeable frequency differences

The dependence on frequency and sound pressure level for both just-noticeable frequency differences and just-noticeable frequency modulations are similar. Though the absolute values for the former are smaller by a factor of three. For the hearing system it is much easier to recognize differences in frequency. A pause between sounds increases the sensitivity. Below 500 Hz, we are able to tell the difference of only about 1 Hz and above this value increases with the frequency and is approximately $0.002f$. [39]

The phenomena is only level dependent below of about 25 dB. With levels lower than that the just-noticeable difference rises with lowering level. The jnd in frequency is about 5 times larger at a sensation level of 5 dB than at 25 dB. The duration of the stimuli also influences the perception. The given data applies for bursts with durations longer than 200 ms. The just-noticeable frequency difference increaes for burst durations shorter than 200 ms. [39]

4.7 Annoyance

Noise assessments have primarly been directed towards finding the risk of hearing damage. A-weighting is correspondingly used for exposure measure. It is an inadequate measure when assessing annoyance especially for low frequency noise. Though low frequency noise has been found to cause annoyance even at relatively low dBA level. [49][50][51]

Annoyance is poorly measured with A-weighted sound pressure level. It is subject to multiple other characteristics of noise rather than the risk of hearing damage due to e.g. level and exposure time. However, some of the same parameters could strenghten annoyance. [50]

Tonal components in noise are a significant cause of annoyance. The experienced annoyance increases, when the number of tones is raised. [50]

5 Tonality analysis

In order to assess tonality, rules are needed for defining when the received noise can be considered tonal. For this purpose several standards have been created. In this paper the IEC 61400-11 edition 3.0 standard [38] for assessing wind turbine acoustic tonal noise is reviewed in detail. Mesurements and calculations of this work are done accordingly. As a comparison also ETSU standard [6] and Joint Nordic Method for wind turbine noise [52] in addition with the ISO standard for environmental noise [53] are briefly reviewed. In addition the general rules for determining tonality of environmental noise in Finland are presented.

Narrow band analysis is needed when determining the presence of tones. It provides more precise method for analysis instead of using predefined octave or third-octave bands.

5.1 IEC 61400-11 edition 3

Narrow band analysis is done from a noise emission measurement recording. This is because generally no commercial sound level meter is capable of analysing tonality using the standardised calculation method.

5.1.1 General method

The flowchart in figure 29 describes the general course of the analysis step by step. Indivual operations are then explained in detail in the following sections.

There are some requirements for the analysis, which is limited to frequency range from 20 Hz to 11200 Hz. The recording is divided into 10 s energy averaged spectra, which are then sorted into wind speed bins. Therefore the tonal analysis has to cover the same wind speed range as the actual measurement. The minimum amount of spectra required for a given wind speed bin in order to determine the tonal audibility is six. Smaller amount would lead to inconclusive results.

The standard requires a narrowband analysis to be made of the background noise for each wind speed bin. This is done for evaluation that no tones originate from anywhere else other than the wind turbine. If no tones are found no correction for broadband background noise is made.

The basis of the analysis is to find tones that can be considered coming from the same origin. The standard consideres the criterion fulfilled, if identified tones are within an interval ±25% of the critical band centered at the tone frequency. For each spectrum i with an identified tone the following are determined in each wind speed bin k:

- The sound pressure level of the tone $L_{pt,i,k}$
- The sound pressure level of the masking noise $L_{pn,i,k}$ in the critical band
- The tonality $\Delta L_{tn,i,k}$
- The tonal audibility $\Delta L_{a,i,k}$

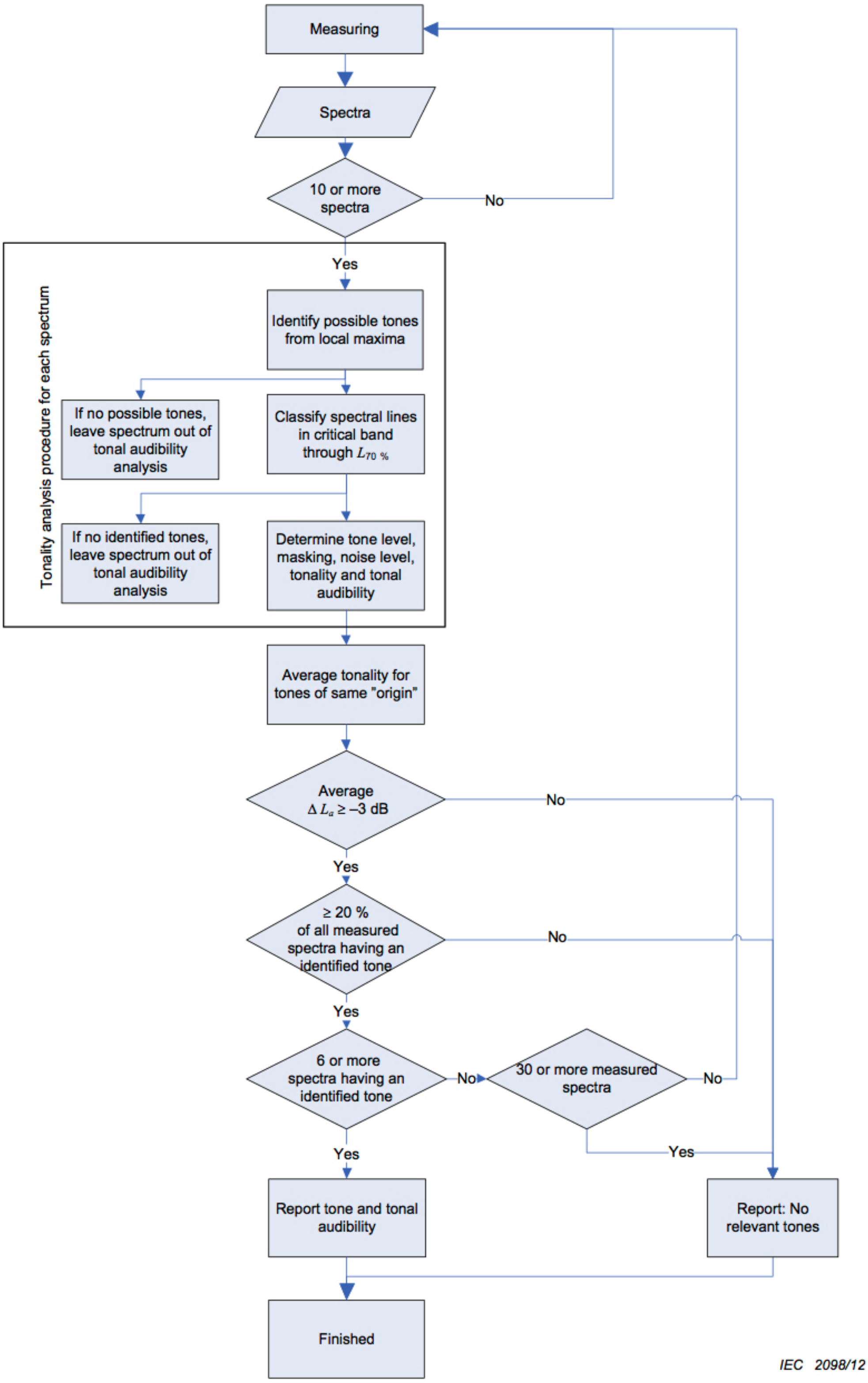


Figure 29: Flowchart for tonal analysis [38]

Then the overall tonal audibility $\Delta L_{a,k}$ is determined in each wind speed bin for tones of the same origin by calculating the energy average of the individual tonal audibilities. Only spectra with identified tones are included.

5.1.2 Finding a possible tone

First step in the procedure is to find possible tones from the 10 s energy averaged spectra. This is done in order to reduce the work load needed for more detailed calculations later on. The following steps are done for every local maxima found in the spectrum:

a) The critical band centered on the maxima is calculated with equation 22

b) The average energy in the critical band is calculated, excluding the local maximum and two adjacent lines

c) If the local maximum is more than 6 dB above the average energy, then it is classified as a possible tone.

5.1.3 Classification of spectral lines

The critical band width centered in the frequency of every possible tone, is used for classification of the spectral lines. Exceptions are the possible tones with frequencies between 20 Hz and 70 Hz. The calculated critical band's lower limit would be below 20 Hz, therefore for them it is fixed between 20 Hz and 120 Hz. Since the frequency resolution of the FFT causes the spectral lines to have width between 1-2 Hz, it is needed to define boundary conditions for the lower and upper thresholds. A line is included in the critical band, if the line's centre frequency is included in the calculated band. From this step forward the contents of one critical band do not influence any other band.

Within each critical band spectral lines are classified as tone, masking or neither, using the following procedure.

a) The energy averaged sound pressure level of 70% of the spectral lines with the lowest levels ($L_{70\%}$) is calculated.

b) The criterion level, which is equal to $L_{70\%} + 6\text{dB}$, is determined (figure 30)

- A line is classified as masking if its level is less than the criterion level. $L_{pn,avg}$ is the energy average of all the lines classified as masking.
- A line is classified as tone if its level exceeds $L_{pn,avg} + 6\text{dB}$.
- If there are multiple lines classified as tone, the line with the greatest level is identified. Adjacent lines are then only considered as tone lines, if their levels are within 10dB of the highest level.
- A line is classified as neither, if it is neither tone nor masking. They are ignored in further analysis.

In figure 31 the determination criterion for all spectral lines is illustrated.

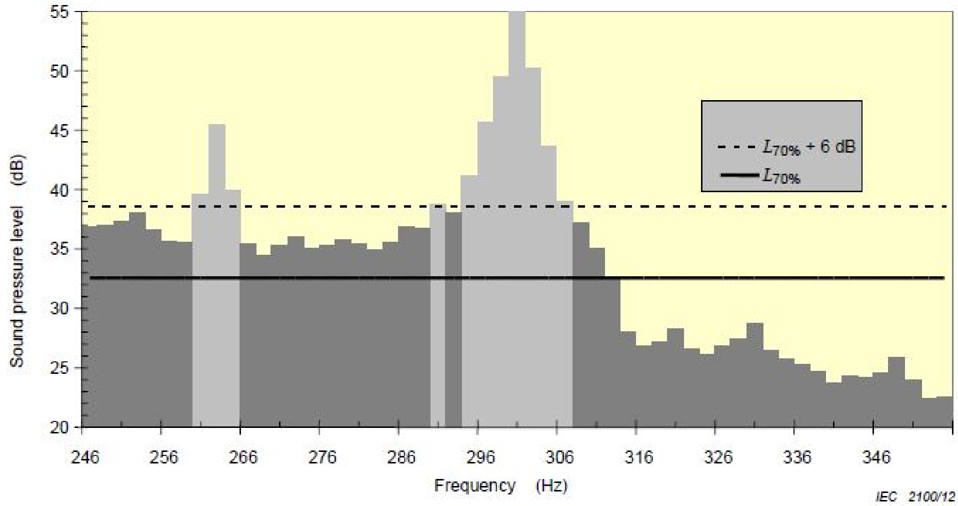


Figure 30: $L_{70\%}$ + 6 dB criterion [38]

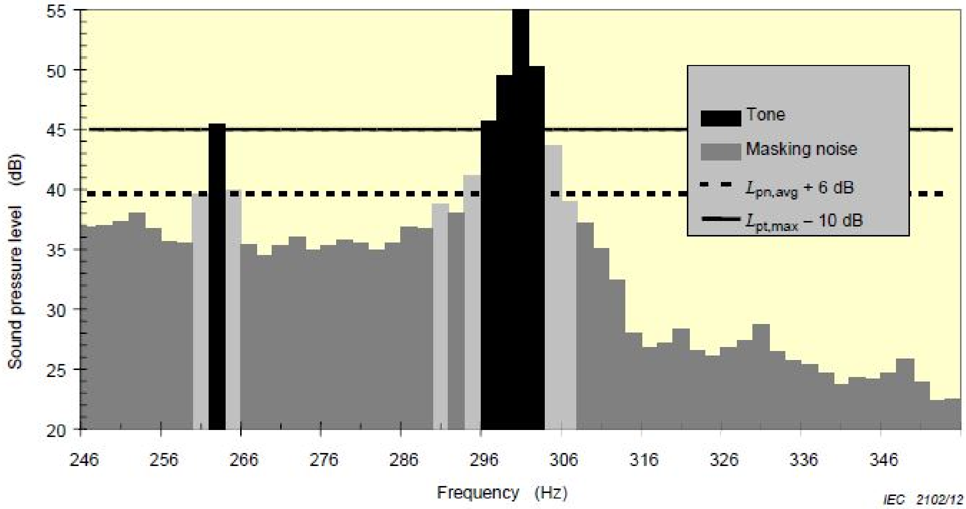


Figure 31: Classification of all spectral lines [38]

5.1.4 Determination of levels

Identified spectral lines vary in magnitude, therefore it is needed to determine the levels of the masking noise and the tones.

The sound pressure level of the tone ($L_{pt,i,k}$) is calculated by energy summing all spectral lines identified as tones within the critical band Bc. If more than one line is identified, the energy sum is divided by 1.5 for correction for usage of the Hanning window.

The masking noise level $L_{pn,i,k}$ is calculated as

$$L_{pn,i,k} = L_{pn,avg,i,k} + 10\log_{10}\left[\frac{Bc}{Bn}\right], \tag{25}$$

where the effective noise bandwidth Bn is $1.5f_{res}$, which includes a correction for the use of the Hanning window. f_res is the frequency resolution of the FFT.

5.1.5 Determination of tonal audibility

Before it is possible to determine whether a tone is audible or not, a unit called tonality has to be calculated. Tonality is the difference between the tone level and the masking noise level and is calculated as

$$\Delta L_{tn,i,k} = L_{pt,i,k} - L_{pn,i,k}. \tag{26}$$

The tonal audibility $\Delta L_{a,i,k}$ is then defined as

$$\Delta L_{a,i,k} = \Delta L_{tn,i,k} - L_a, \tag{27}$$

where L_a is the frequency dependent audibility criterion. L_a is used as a correction for compensation of the response of the human ear to tones of different frequency. It describes the level at which an average listener is just able to hear the tone [6]. It is defined as

$$L_a = -2 - \log_{10}\left[1 + \left(\frac{f_{max}}{502}\right)^{2,5}\right], \tag{28}$$

where f_{max} is the frequency of the tone maximum.

The $\Delta L_{a,i,k}$ are energy averaged into one $\Delta L_{a,k}$ for every tone from the same origin in each wind speed bin. Thereby the audible tones are divided into groups based only on the wind speed.

Tones are reported audible if the meet the condition

$$\Delta L_{a,k} \geq -3,0 \text{ dB}. \tag{29}$$

There are two exceptions. If less than 20% of 10 spectra or more contain identified tones, then no audible tones are reported. If more than 20% but less than 6 spectra contain identified tone, then more measurements are needed. Up to 30 spectra may be needed before conclusion can be made.

5.2 IEC 61400-11 edition 2

IEC 61400 edition 2.1 [54] is the previous version of the method reviewed in the previous section. The tonal audibility assessment is not so complex and has some simplifications compared to the newest edition. The standard states that it is only suitable for detection of narrow band tones. Broad tones consisting of many spectral lines or masking noise with very steep gradient may not give correct results.

The analysis requires two one-minute periods for each wind speed bin. They are divided into 12 ten-second periods, from which 12 energy averaged narrowband spectra are obtained using the Hanning window. The frequency resolution limits are determined for two regions which are shown in table 1.

Table 1: Frequency resolution for ed. 2.1

Frequency Hz	**Less than 2000**	**2000 – 5000**
Frequency resolution	2 to 5 Hz	2 to 12.5 Hz

The classification of spectral lines and also calculation of tone level and masking noise level are identical with the edition 3.0. Unlike in the newer version, the background noise is corrected and the level needs to be at least 6 dB lower than the noise generated by the wind turbine. Otherwise it has to be recorded that the masking noise is influenced by background noise. Respective to the turbine noise analysis the background noise has to be analysed using two 1-minute measurements for each wind speed bin.

Determination of tonality and audibility are done in the same way as in the 3.0 edition. Though the extra exception of not having enough analysed spectra are excluded.

5.3 Joint Nordic Method

As the IEC standard also the Joint Nordic Method (JNM) for assessing the audibility of tones in noise [52] requires a narrow-band A-weighted frequency analysis preferebly done with FFT and the Hanning-window. Included is also determination of average sound pressure level of the tones and masking noise within each critical band. The audibility of tones and a penalty is calculated following the guidelines.

The method does not give an exact frequency resolution for the analysis, but the effective bandwidth must be smaller than 5% of the bandwidth of the lowest critical band with tonal components. If the detected tone level is below the hearing threshold, it is disregarded.

Critical band is centered at the tone frequency. The bandwidth determination differs a bit from the IEC method. The dependancy on the centre frequency f_c is shown in table 2. This is a simplified version of the bandwidth calculated with the equation 22. In figure 32 is shown the frequency dependent level difference of the two definitions for the critical band.

Table 2: Widths of critical band

Centre frequency, f_c	**50-500 Hz**	**Above 500 Hz**
Bandwidth	100 Hz	20% of f_c

As in the IEC method the spectral lines are divided into tone lines, masking lines or neither. Tones are defined as all local maxima with a 3 dB bandwidth smaller than 10% of the bandwidth of the actual critical band (figure 33). Frequency variation of up to 10% of the critical bandwidth is allowed between detected tones. Total tone level is calculated as the energy sum of all tones within the same critical band.

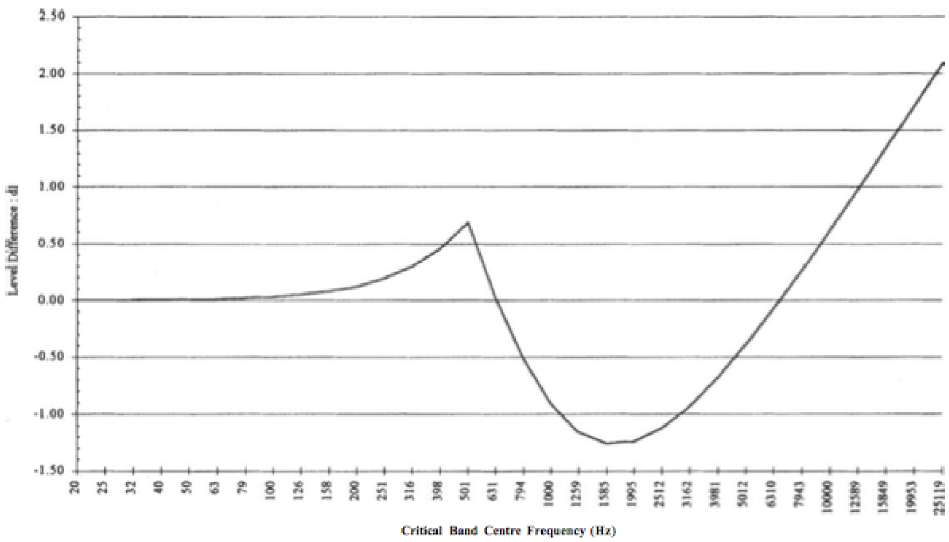


Figure 32: Level difference of critical bandwidths defined by IEC 61400 and the Joint Nordic Method [6]

Masking noise sound pressure level is calculated in the same way as in the IEC method with equation 25.

The tonal audibility is determined as in dB above the masking threshold with the combination of equations 27 and 28. The tone-corrected rating level is calculated by adding a penalty k to the A-weighted equivalent noise level L_{Aeq} of the noise source. In figure 34 k is plotted as a function of frequency and difference of the tonal level and masking noise level.

The objective method for assessing the audibility of tones in noise in ISO 1996-2:2007 [53] is in outline the same as in the JNM.

5.4 ETSU-R-97

The ETSU-R-97 [6] is a guideline used in the United Kingdom for assessment and rating of noise from wind turbines. The method is generally based on the Joint Nordic Method. It requires 2 minutes of uninterrupted clean A-weighted recording for each tonal assessment. A FFT is used to the data using a Hanning window. Defined frequency resolution is 3.0 + 0.5 Hz and the analysis bandwidth is 2 kHz.

As the precious methods the analysis is based on classification of spectral lines within the critical band, which is done in a similar way as in the IEC 61400. Definition of the critical band is identical to the JNM. The process is repeated for every tonal peak in the spectrum.

5.5 Third octave band tonality analysis

Environmental noise measurement guide [55] of the Finnish Ministry of Environment has introduced a simpler way to assess the existence of tonal noise. Instead of

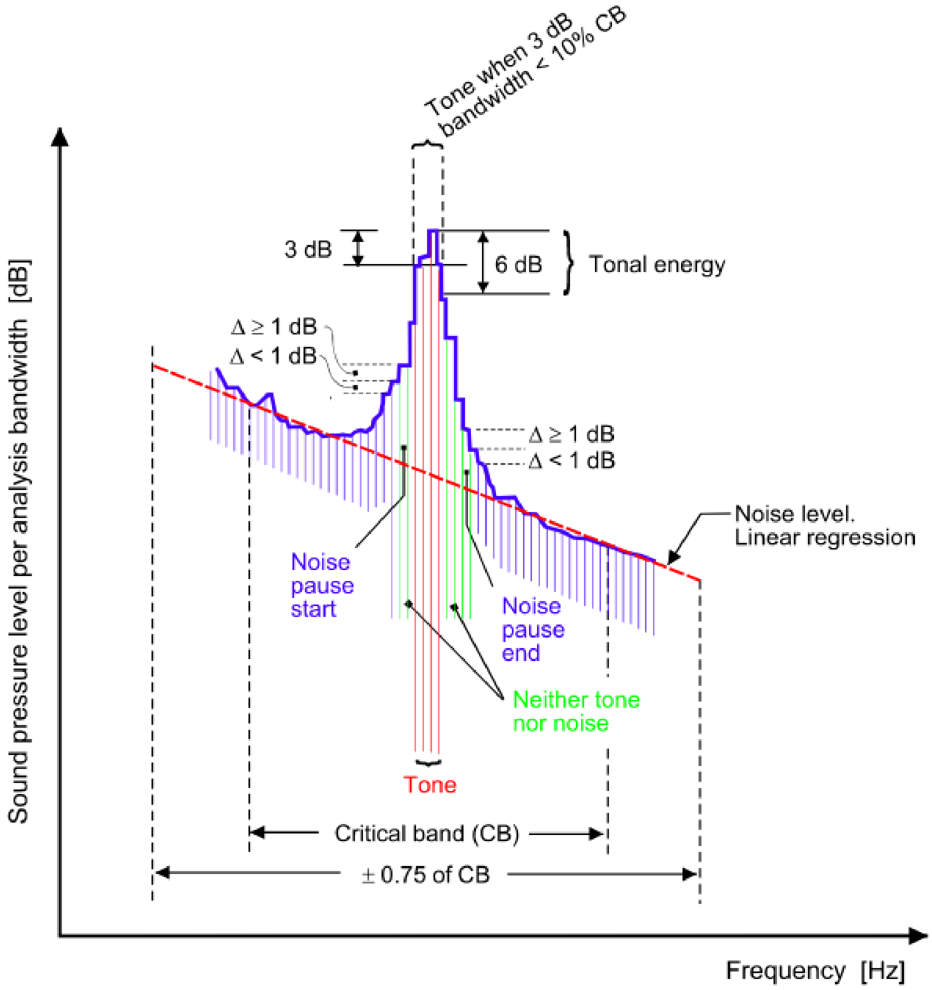


Figure 33: Definitions of tones, noise and lines that are neither [52]

a narrowband analysis a less complex method is based on measuring third-octave bands.

If a hearing perception does not unambiguously preclude the possibility of tonal components, it is possible to exclude them with a simple analysis. The noise is tonal if the magnitude of a third-octave band is at least 5 dB higher than the adjacent bands.

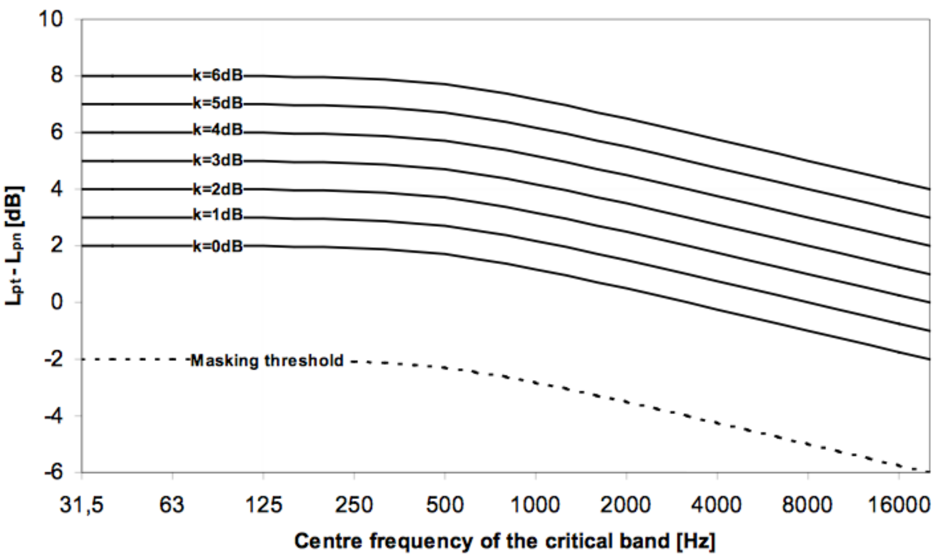


Figure 34: Curves for determining the penalty k [52]

6 Wind turbine measurement and results

The basis of this work is to analyse an existing wind turbine. The wind farm location, measurement procedure and tonal audibility analysis results are presented in this section.

6.1 Measurement

The goal of the performed measurement was to determine the sound power level of the given turbine. The measurement of the wind turbine was done according to the IEC 61400-11 standard. Although in the tonal audibility analysis it is not needed to use the data measured by the sound level meter, but to use a recording for separate narrowband assessment. Nevertheless with the proper measurement procedure also the recording data is obtained in conditions stated by the standard thus being comparable with other similar measurements.

In this section the wind farm in Pori is presented with details about the weather conditions and the measured turbine. Also the measurement procedure is introduced briefly with the main facts about the used acoustic instruments.

6.1.1 Wind farm

The wind farm is owned by Tuuliwatti Oy and located in Pori Peittoo. It consists of 12 Gamesa G128 4.5 MW turbines of with tower height of 140 meters and rotor diameter of 128 meters [56]. Location of the site is in western Finland by the coast line and provides various wind conditions. The surrounding area is lightly inhabited without heavy traffic. Some industry and industrial landfill is also present. In figure 35 there is a map of the area including the location of the measured WT8 turbine and the used measurement position.

Onshore the wind speed is generally lower than over the sea, but the differences become smaller with increasing height [57]. Gusts are common in the area. Background noise at the farm area is mainly generated by interaction of wind and the ground surface. Low level of background noise can make the sound emitted from the turbines more annoying compared to other sites [58]. Still, increase in wind speed generally means also an corresponding increase in background wind noise in foliage, which assists to acoustically mask the wind farm noise [59]

6.1.2 Acoustic measurement procedure

The standard states that the equipment used in an acoustic measurement for determination of narrow band spectra need to fulfill the following criterion:

- class 1 sound level meter (Cirrus optimus green, 32bit 96 kHz audio)
  - meets the requirements of IEC 61672
  - the diameter of the microphone diaphragm is smaller than 13 mm

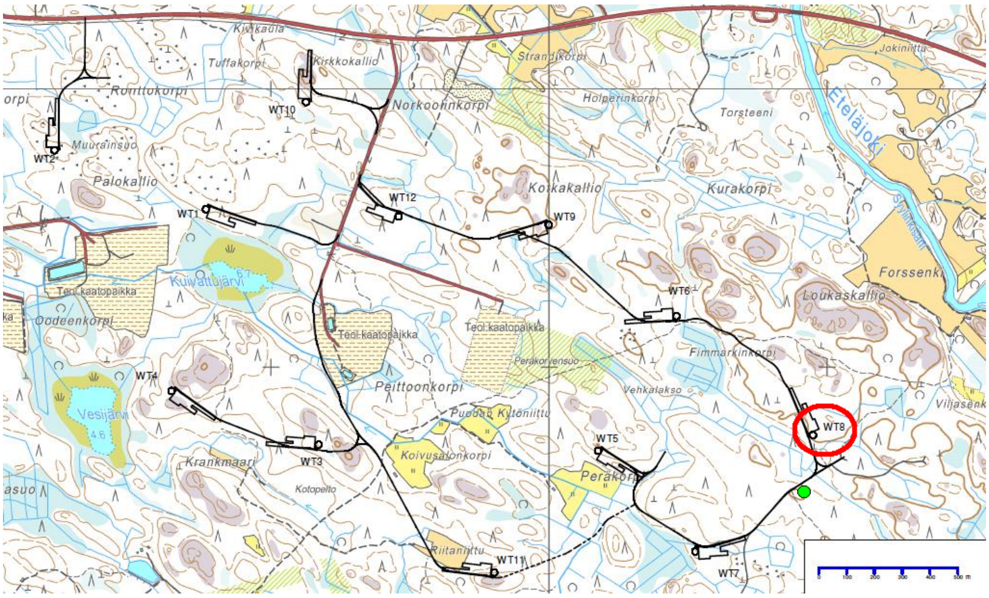


Figure 35: Map of the wind farm

– a constant frequency response over the 1/3-octave bands from 20 Hz to 10 kHz

- measurement board, diameter 1 m
- windscreen
- secondary wind screen
- acoustical calibrator that meets the requirements of IEC 60942:2003 class 1 (Cirrus CR:515)
- data recording system that meets the requirements of IEC 61672 class 1

One mandatory downwind measurement position was used (figure 36). It is identified as the reference position. The tolerance for the direction of the position is ±15° relative to the downwind direction of the turbine nacelle or the yaw position. This boundary must not be exceeded during the whole length of the measurement. The horizontal distance R_0 is determined by

$$R_0 = H + \frac{D}{2}, \tag{30}$$

where H is the height of the rotor centre and D is the diameter of the rotor. Tolerance for the distance is ±20 % and maximum ±30 m. The used measurement position was 183 meters from the turbine (figure 35, green circle), which is within the limits.

The minimum wind speed at hub height for sound power level measurement is from 0.8 to 1.3 times the wind speed at 85 % of maximum power. For the given turbine 85 % of the maximum power is 3.8 MW and wind speed needed is around 10 m/s. Calculated minimum wind speed varies between 8 m/s and 13 m/s. Low and too high wind speeds and also rain obstructs acoustic measurements.

In order to determine the level of background noise, the wind turbine needs to be stopped immediately before or after each measurement series. The same measurement set-up is used and the background noise measurement needs to cover the same wind speed range as for the total noise. The recording is then used to make sure tones are not generated by the interaction between the wind and the environment.

Minimum amount of measured averages for both total noise and background noise is 180. At least 10 measurements have to be made in each wind speed bin.

Since the measurement needs to be done during high wind velocity, it is needed to protect the microphone from direct airflow. This was done with a windscreen, which is a half open cell foam sphere with a diameter of 90 mm. By the standard it is required to use a single windscreen, but due to the wind conditions at the site a secondary windscreen was necessary.

The measurement board is made from acoustically hard material. It has to be circular and have a diameter of at least 1 meter. Gaps or edges under the board should be levelled out by adding soil underneath and over the sides. The microphone is placed in the middle with the windscreen centered on top.

6.2 Results

Two sets of measurements were done in the wind farm for this thesis. In this section the results of the IEC 61400-11 tonality analysis are presented. All the results are calculated from an audio recording.

The preliminary measurements were conducted on March 11-12 2014 on WT11 and WT4, which had the best locations of the already erected turbines for the prevailing wind direction. A tonality analysis was not performed on the measured data, because the turbines were found subsequently to be defective.

A second set of measurements were performed in June 2014 for WT8. The weather conditions were optimal for determining the sound power level. This time all the other turbines were stopped in order to make sure their influence was fully excluded. Results of this measurement is included in this section. Nevertheless it needs to be noted that afterwards major fixes to the controlling software were performed.

The results shown here are not synchronized with the wind speed. Therefore the spectra's connection to the wind speed is not taken into account. The data from the turbine was logged with a separate system that was not connected with the audio recording.

6.2.1 WT8

The results of the WT8 measurements are presented step by step following the outline of the standard.

Figure 36: Measurement set-up

The magnitude of the spectra is not calibrated and therefore only the relative strengths of the frequency bars are correct. Final results of the analysis are summarised in the end.

Minimum amount of calculated spectra in the narrow band analysis is 30. In this section the calculation phases of only a single spectrum are presented in detail. The values of the 30th spectrum of the recording are calculated with frequency resolution of 2 Hz. The frequency content of the entire spectrum is presented in figure 37. The

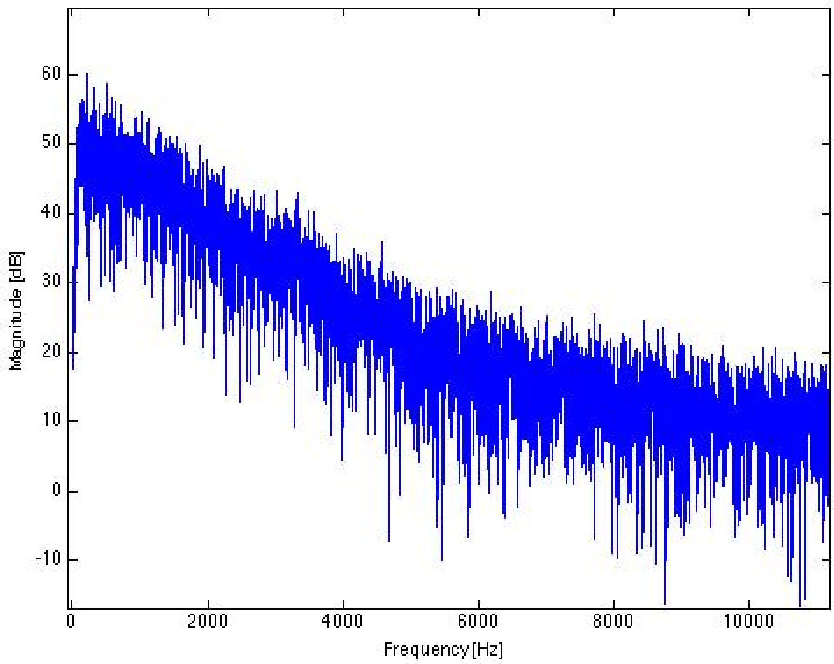


Figure 37: Frequency spectrum

analysis is based on calculating sound levels within a critical band centered at a certain frequency. The first step is to narrow down the data by determining whether possible tones exist or not. This is done by the method described in section 5.1.2. In the given spectrum there are 84 local maxima that are classified as possible tones ranging from 210 Hz to 10340 Hz.

The next step is to classify the spectral lines within the critical band centered in the frequency of every possible tone (section 5.1.3). As an example the critical band of the possible tone at 336 Hz and 58.3 dB is shown in figure 38. The critical bandwidth is 108 Hz and the limits are 284 Hz and 388 Hz. The levels used in the calculation of the given band are shown in table 3. In figure 39 the level $L_{70} + 6\text{dB}$ is plotted, which is the criterion level for masking bars. $L_{pn,avg}$ is the energy average of all lines classified as masking. A line is classified as a tone if its level exceeds $L_{pn,avg} + 6\text{dB}$. In figure 40 is plotted the threshold level for tones and actual lines are highlighted. Highest line of the band at 336 Hz is chosen as the tone frequency. Because of the calculation procedure, the same tone is possible to be considered as

Variable	Level [dB]
Average energy	49.7
L_{70}	47.2
$L_{pn,avg}$	48.5
$L_{pt,30,k}$	61.2
$L_{pn,30,k}$	64.1
$\Delta L_{tn,30,k}$	-2.8
$\Delta L_{a,30,k}$	-0.71

Table 3: Levels used in classification of spectral lines for 336 Hz local maxima

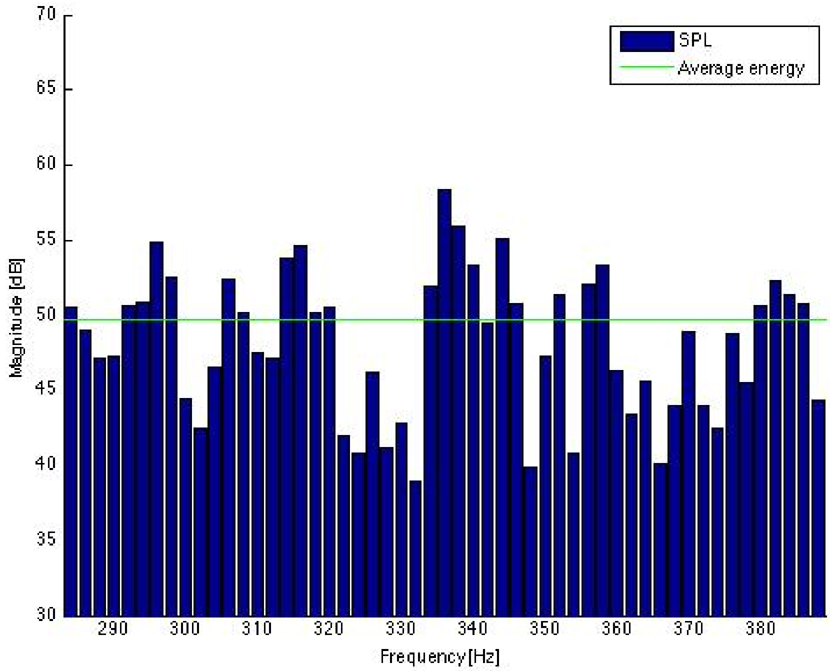


Figure 38: Average energy of the spectrum

a tone for more than one critical band that are formed around each possible tone. Therefore duplicate tones are excluded from further calculations.

In order to determine the level of the tone $L_{tn,j,k}$, the energies of all spectral lines classified as tones are summed together. Because more than one line was found the sum is divided by 1.5. This is done for correcting the usage of the Hanning window.

Determination of masking level $L_{pn,j,k}$, tonality $\Delta L_{tn,j,k}$ and finally tonal audibility $\Delta L_{a,j,k}$ are done according to equations 25, 26 and 27. Results are presented in table 3. The tonal audibility of -0.71 dB is higher than the threshold for audibility -3.0 dB mentioned in the standard, therefore this is considered as an identified tone.

Before it is possible to state that 336 Hz is an audible tone, iteration is needed.

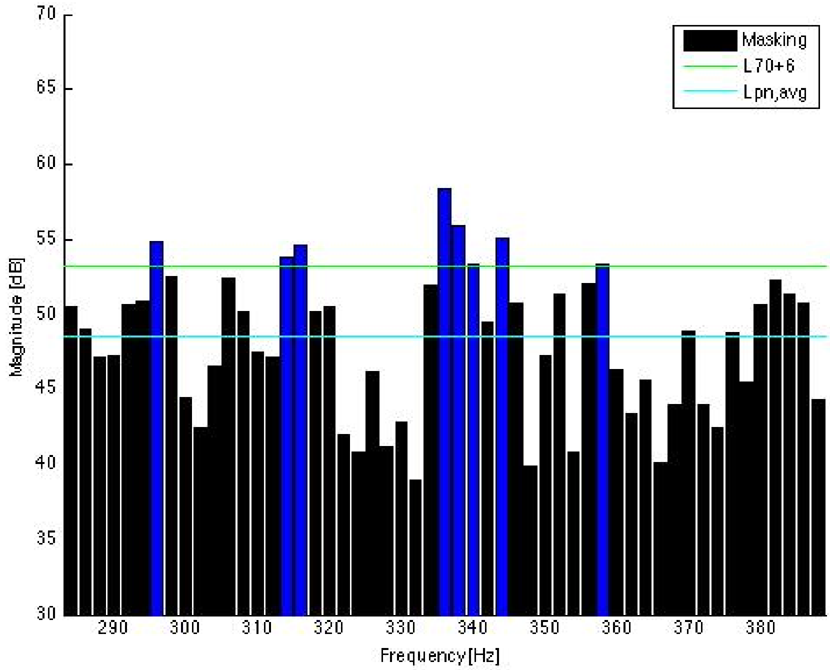


Figure 39: Masking lines

Minimum six occurences of a tone in different spectra or others considered coming from the same origin are needed for making the final decision whether to report the tone as audible or not. Fluctuation of ±25% is allowed within the critical band centered at the tone. Basically if there are identified tones in other spectra between 309 Hz and 363. Maximum one tone from each spectrum is included in the calculation. The tonal audibilities $\Delta L_{a,j,k}$ are then energy averaged into a single value $\Delta L_{a,k}$. If the average is higher than -3.0 dB tonal audibility is reported. Then the identified tone with the highest individual tonal audibility is chosen as the reported frequency. The classification of the lines of all the spectra is illustrated in figures 41, 42, 43, 44, 45 and 46. Further details about the intermediate values of the calculation are provided in tables 4 and 5.

As can be seen in table 4 , the observed frequency 336 Hz does not have the highest tonal audibility value. Only one tone can be reported in the critical band's range and the one with the highest $\Delta L_{a,k}$ is chosen. Therefore 346 Hz is not chosen even though it has the highest individual tonal audibility. When the center frequency changes, also the observed band alters and it leads to variation in the calculated average tonal audibility. Accordingly, the band of 346 Hz has lower tonal audibility than the band of 336 Hz.

According to the analysis audible tones are detected at frequencies 84, 198, 272, 336, 482, 536, 634, 680, 900, 1098, 1236, 1354, 1512, 1680, 2006, 2294, 2686, 2806, 3748, 3968, 4508, 4912, 5768, 6678 and 8598 Hz. This result is obtained before verification that the tones do not originate from background noise.

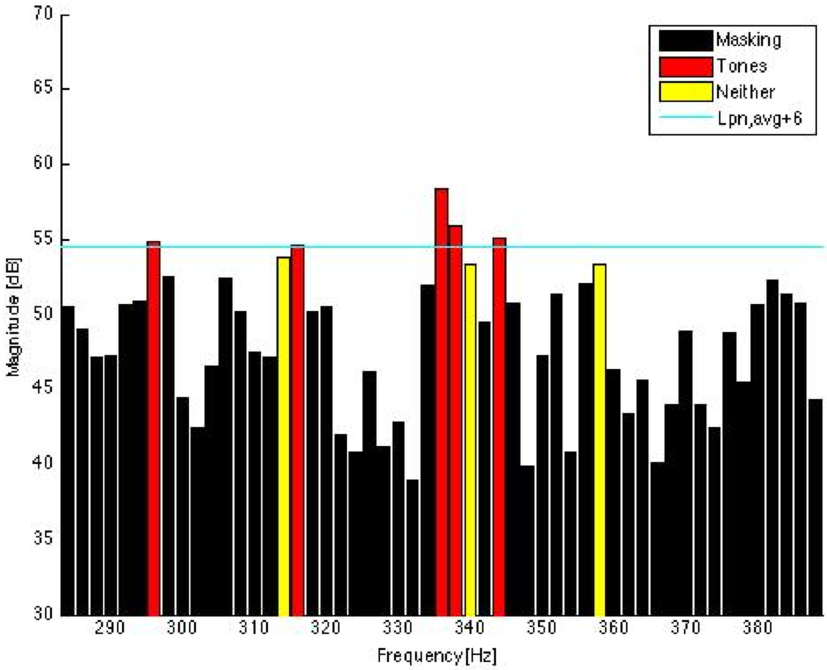


Figure 40: Tone lines

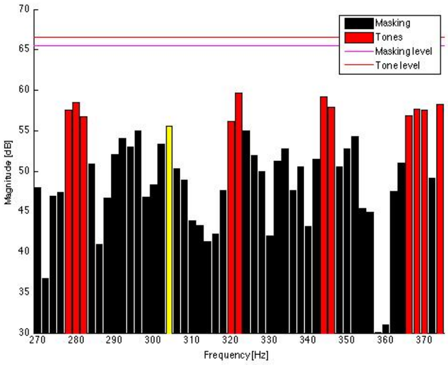
Background noise

In order to determine if tones originate from the background noise, the same analysis is performed on recording of the background noise. All wind turbines were stopped during the recording period, so it describes the prevalent noise conditions well.

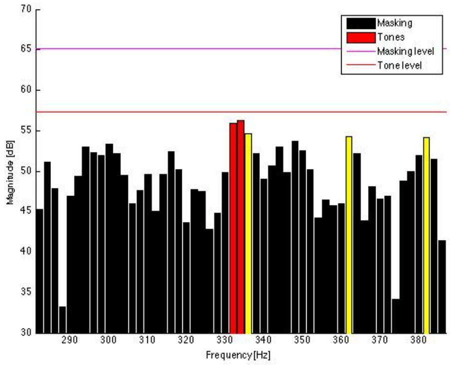
In figure 47 is shown a 10 second spectrum of background noise. No clear frequency peaks are visible, which applies to all analysed samples of the recording.

As an example of identified tones, the critical bands of 92 Hz peaks are presented in figure 48. The tone is found in four different spectra.

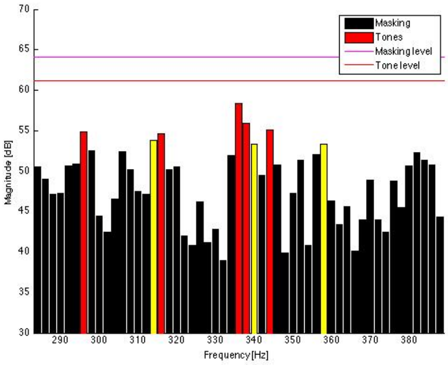
The results show that audible tones are detected at frequencies 92, 150, 246, 328, 370, 402, 438, 512, 546, 680, 760, 812, 866, 904, 984, 1036, 1150, 1348, 1582, 2124, 2320, 2796, 3646, 4662, 5416 and 8504 Hz.



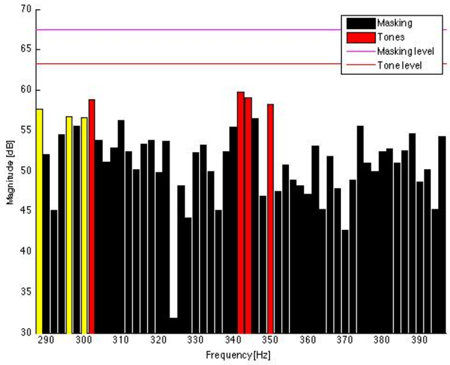
(a) 322 Hz, 1st spectrum



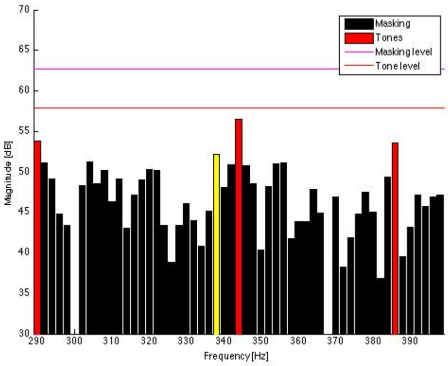
(b) 334 Hz, 58th spectrum



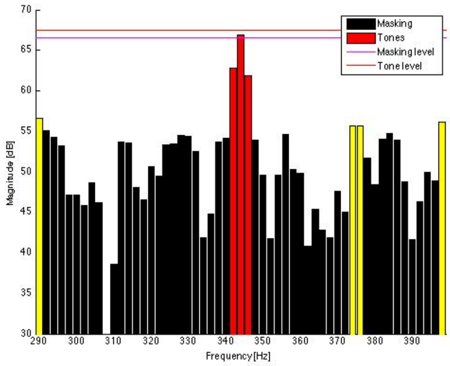
(c) 336 Hz, 30th spectrum



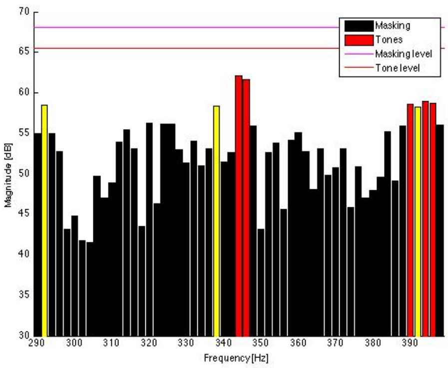
(d) 342 Hz, 43rd spectrum



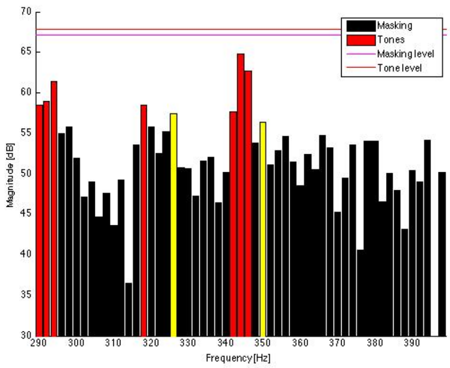
(e) 344 Hz, 4th spectrum



(f) 344 Hz, 7th spectrum

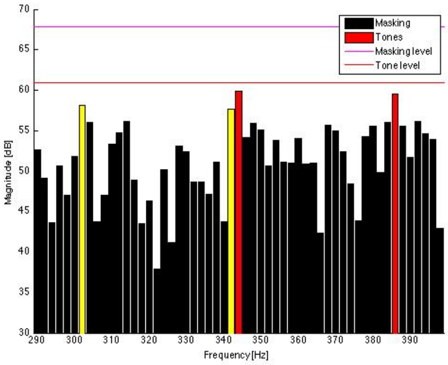


(g) 344 Hz, 8th spectrum

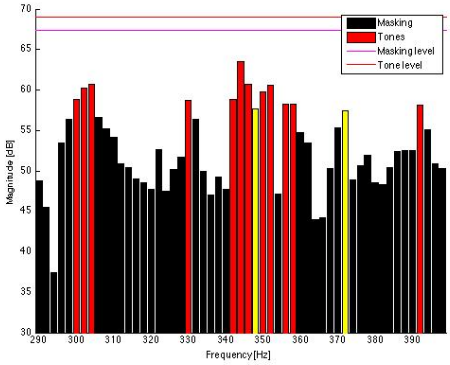


(h) 344 Hz, 17th spectrum

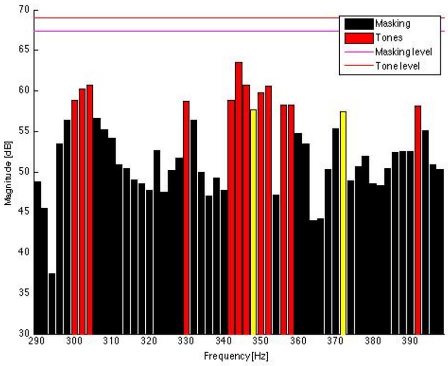
Figure 41: Identified tones of each spectrum



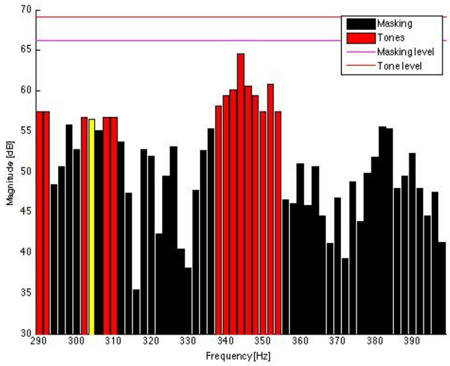
(a) 344 Hz, 25th spectrum



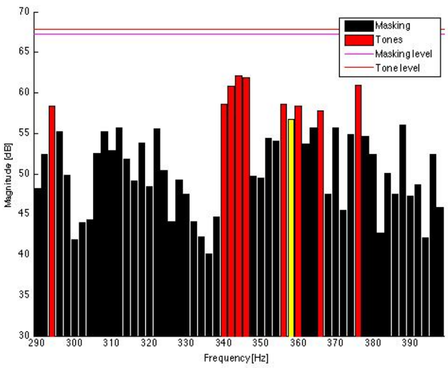
(b) 344 Hz, 26th spectrum



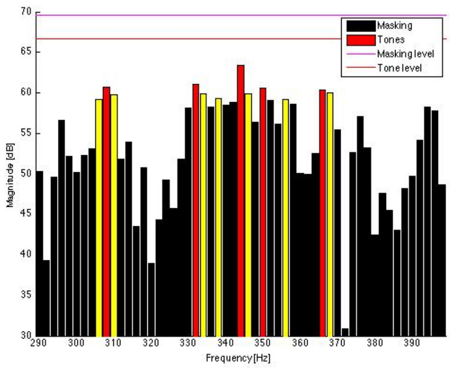
(c) 336 Hz, 29th spectrum



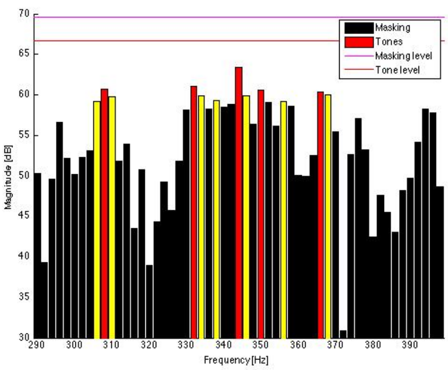
(d) 342 Hz, 33rd spectrum



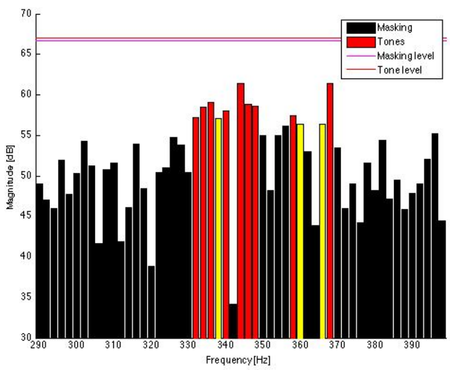
(e) 344 Hz, 38th spectrum



(f) 344 Hz, 39th spectrum

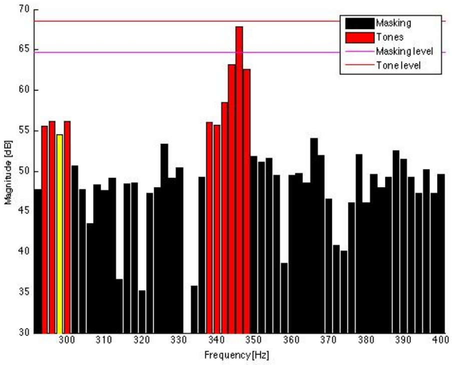


(g) 344 Hz, 47th spectrum

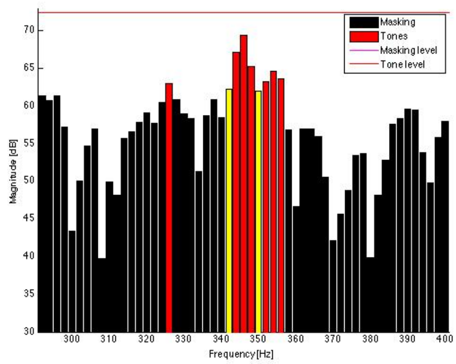


(h) 344 Hz, 52nd spectrum

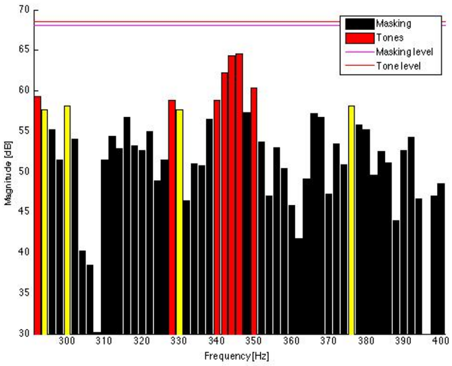
Figure 42: Identified tones of each spectrum



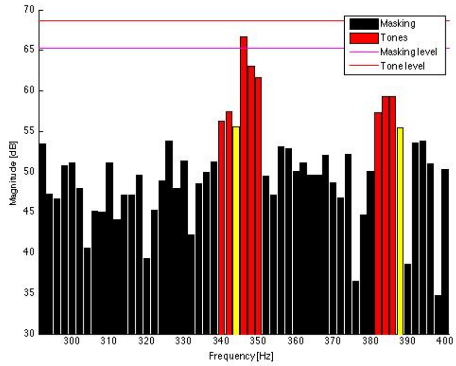
(a) 346 Hz, 6th spectrum



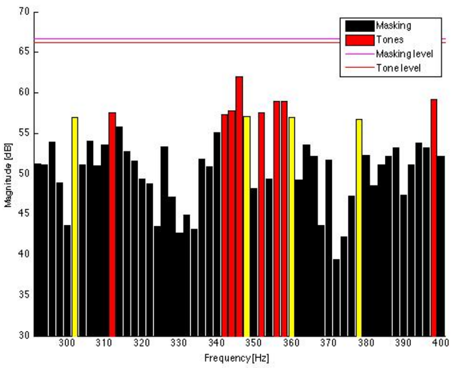
(b) 346 Hz, 15th spectrum



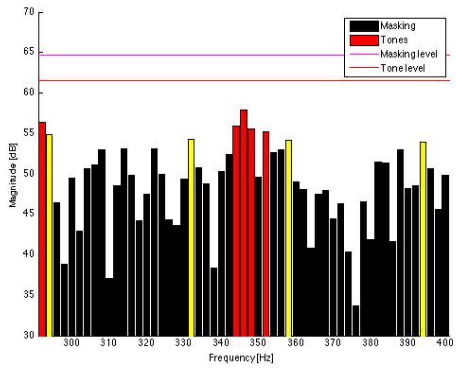
(c) 346 Hz, 22nd spectrum



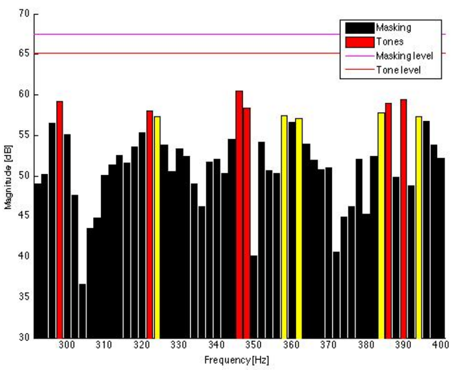
(d) 342 Hz, 43rd spectrum



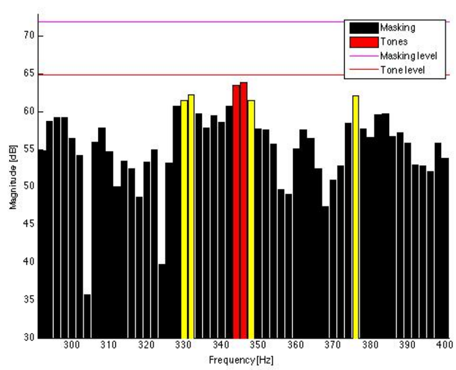
(e) 346 Hz, 27th spectrum



(f) 346 Hz, 32nd spectrum

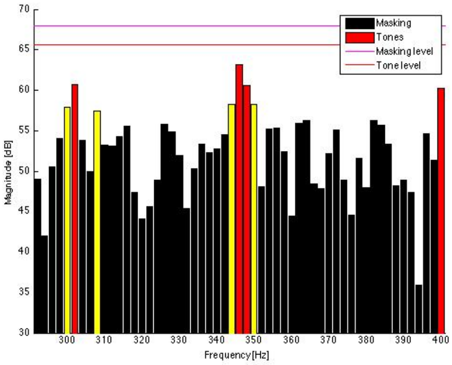


(g) 346 Hz, 6th spectrum

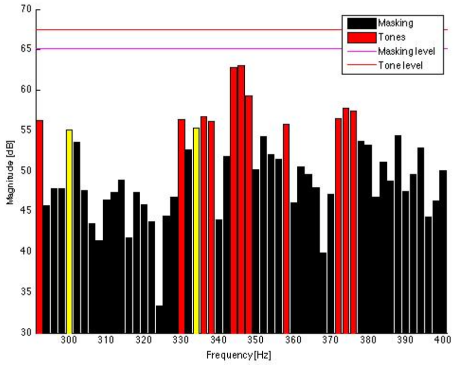


(h) 346 Hz, 40th spectrum

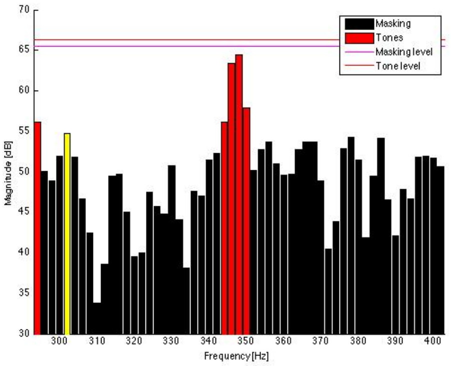
Figure 43: Identified tones of each spectrum



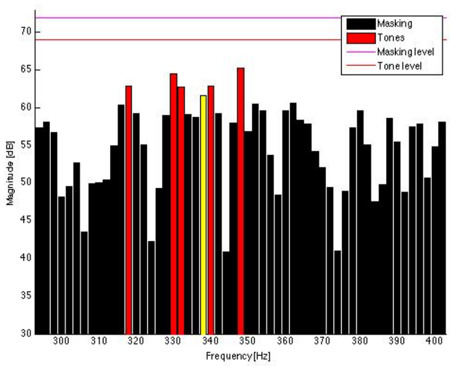
(a) 346 Hz, 42nd spectrum



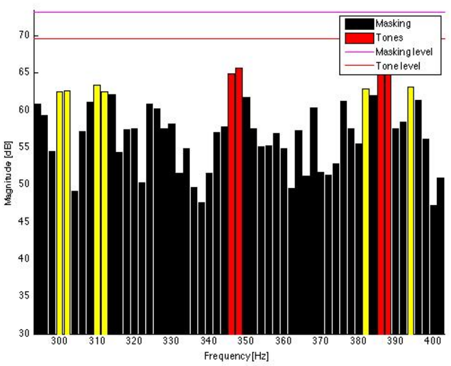
(b) 346 Hz, 49th spectrum



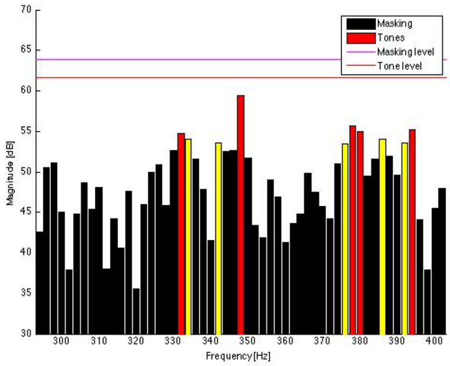
(c) 348 Hz, 5th spectrum



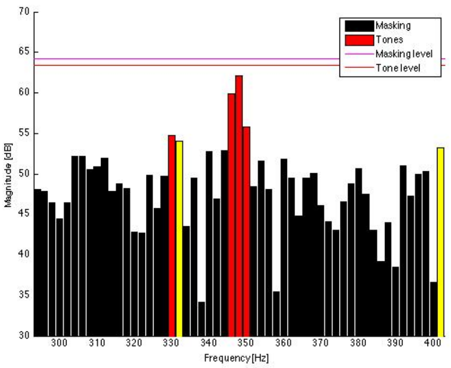
(d) 348 Hz, 10th spectrum



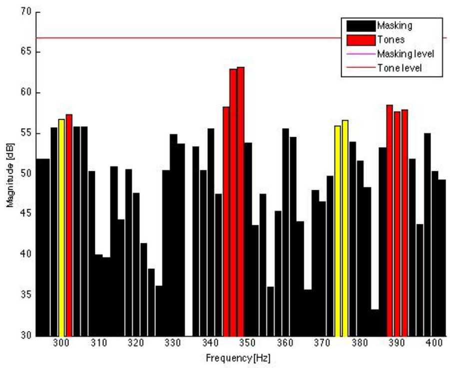
(e) 348 Hz, 13th spectrum



(f) 348 Hz, 19th spectrum

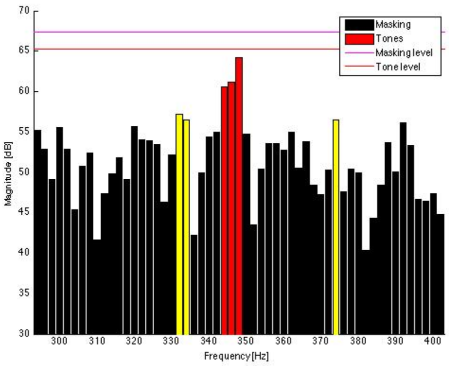


(g) 348 Hz, 23rd spectrum

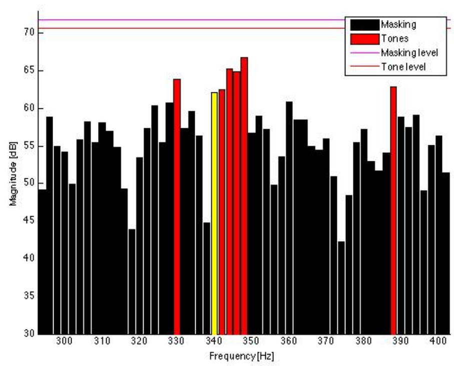


(h) 348 Hz, 28th spectrum

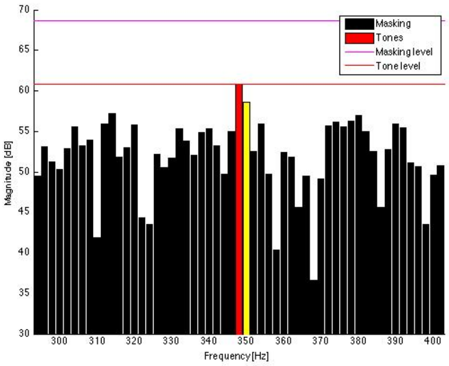
Figure 44: Identified tones of each spectrum



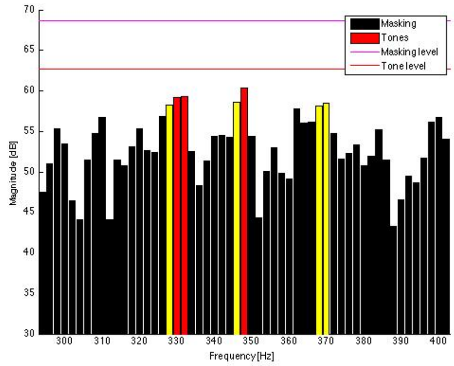
(a) 348 Hz, 34th spectrum



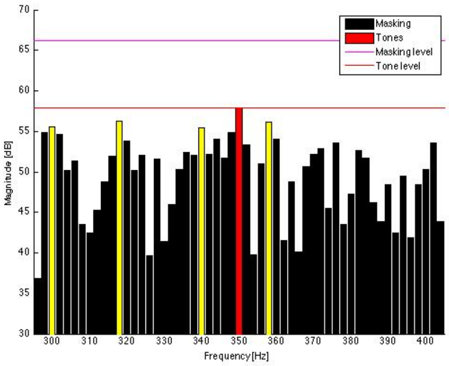
(b) 348 Hz, 46th spectrum



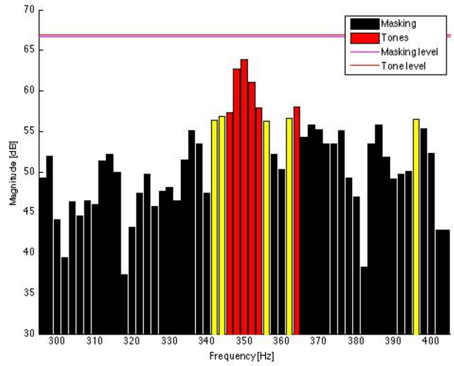
(c) 348 Hz, 51st spectrum



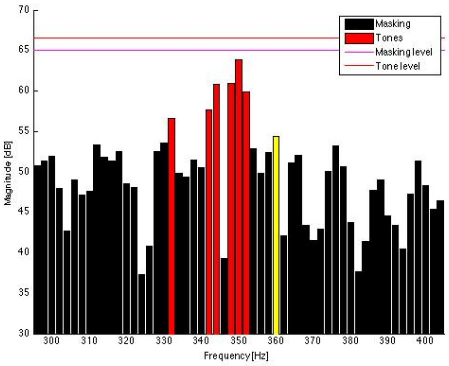
(d) 348 Hz, 53rd spectrum



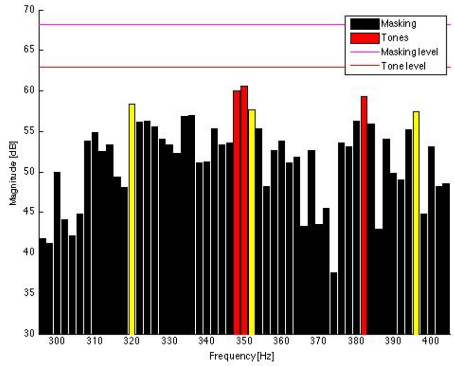
(e) 350 Hz, 3rd spectrum



(f) 350 Hz, 20th spectrum



(g) 350 Hz, 21st spectrum



(h) 350 Hz, 54th spectrum

Figure 45: Identified tones of each spectrum

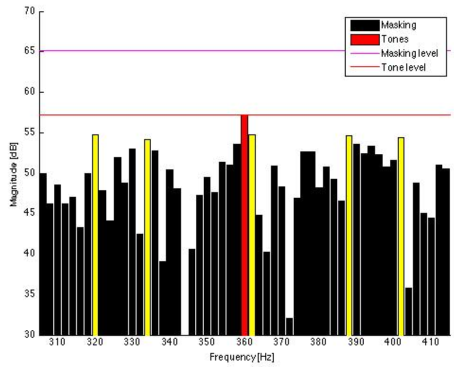


Figure 46: 360 Hz, 18th spectrum

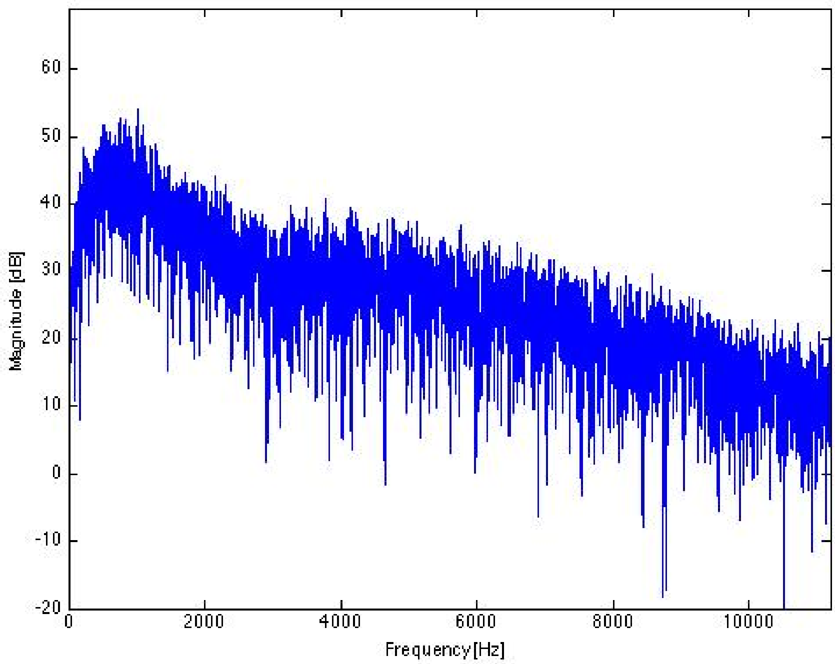


Figure 47: Frequency spectrum of a 10 second sample of background noise

f	322	334	336	342	344	344	344	344	344	344	344
j	1	58	30	43	4	7	8	17	25	26	29
L_{70}	49.0	48.0	47.2	50.5	45.3	49.5	51.3	50.4	50.9	50.4	51.4
$L_{pn,j,k}$	65.5	65.2	64.0	67.5	62.7	66.5	68.1	67.1	68.0	67.9	67.4
$L_{pn,avg}$	50.0	49.6	48.5	51.9	47.2	51.0	52.5	51.5	52.4	52.3	51.8
$L_{pt,j,k}$	66.6	57.3	61.2	63.3	57.9	67.5	65.5	67.8	60.0	61.0	69.0
$\Delta L_{tn,j,k}$	1.1	-7.9	-2.8	-4.2	-4.9	0.9	-2.6	0.7	-7.9	-6.9	1.7
$\Delta L_{a,j,k}$	3.2	-5.7	-0.7	-2.1	-2.7	3.1	-0.4	2.8	-5.8	-4.8	3.8

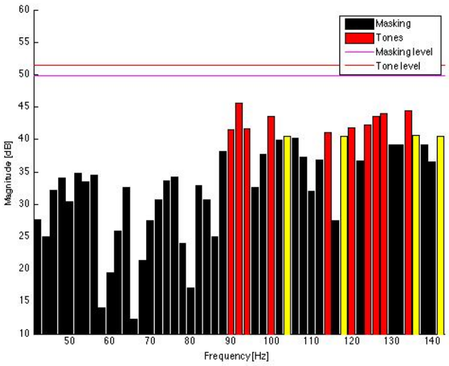
f	344	344	344	344	344	346	346	346	346	346	346
j	33	38	39	47	52	6	15	22	24	27	32
L_{70}	50.4	50.5	53.3	53.0	50.2	48.1	55.5	51.4	48.6	50.5	47.9
$L_{pn,j,k}$	66.2	67.2	70.1	69.6	66.6	64.7	72.5	68.1	65.3	66.7	64.7
$L_{pn,avg}$	50.6	51.6	54.5	54.0	51.0	49.1	56.9	52.5	49.7	51.1	49.1
$L_{pt,j,k}$	69.1	67.8	67.0	66.6	67.0	68.5	72.5	68.5	68.6	66.2	61.5
$\Delta L_{tn,j,k}$	2.9	0.6	-3.1	-3.0	0.4	3.8	0.0	0.4	3.3	-0.5	-3.1
$\Delta L_{a,j,k}$	5.0	2.8	-1.0	-0.8	2.5	6.0	2.2	2.6	5.5	1.6	-1.0

f	346	346	346	346	348	348	348	348	348	348	348
j	36	40	42	49	5	10	13	19	23	28	34
L_{70}	50.9	54.9	51.2	48.8	48.4	54.7	56.4	47.1	47.1	49.8	50.3
$L_{pn,j,k}$	67.5	72.0	68.0	65.1	65.5	71.9	73.1	63.8	64.2	66.7	67.3
$L_{pn,avg}$	51.9	56.4	52.4	49.5	49.9	56.3	57.6	48.2	48.6	51.2	51.8
$L_{pt,j,k}$	65.1	64.9	65.6	67.5	66.3	69.0	69.6	61.6	63.4	66.7	65.3
$\Delta L_{tn,j,k}$	-2.4	-7.0	-2.4	2.4	0.8	-2.9	-3.5	-2.2	-0.8	-0.0	-2.1
$\Delta L_{a,j,k}$	-0.2	-4.9	-0.2	4.6	2.9	-0.7	-1.4	-0.0	1.4	2.1	0.1

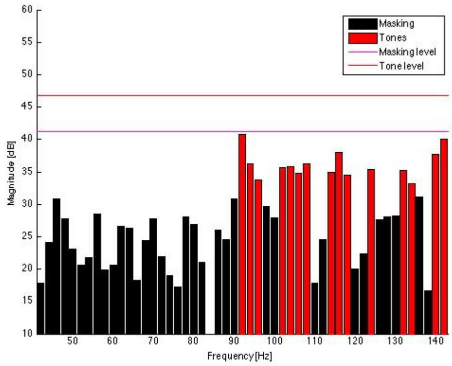
Table 4: Individual levels of critical band centered at 336 Hz

f	348	348	348	350	350	350	350	352	360
j	46	51	53	3	20	21	54	21	18
L_{70}	54.9	51.4	51.8	48.9	50.0	48.1	51.0	47.7	48.1
$L_{pn,j,k}$	71.9	68.7	68.7	66.2	66.7	65.0	68.2	64.4	65.2
$L_{pn,avg}$	56.3	53.1	53.1	50.6	51.1	49.4	52.6	48.7	49.6
$L_{pt,j,k}$	70.7	60.8	62.7	57.9	66.9	66.6	63.0	64.5	57.1
$\Delta L_{tn,j,k}$	-1.2	-7.9	-6.1	-8.2	0.2	1.6	-5.2	0.1	-8.0
$\Delta L_{a,j,k}$	0.9	-5.7	-3.9	-6.1	2.4	3.7	-3.1	2.2	-5.9

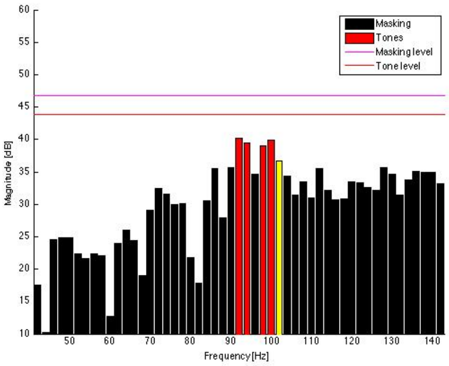
Table 5: Individual levels of critical band centered at 336 Hz



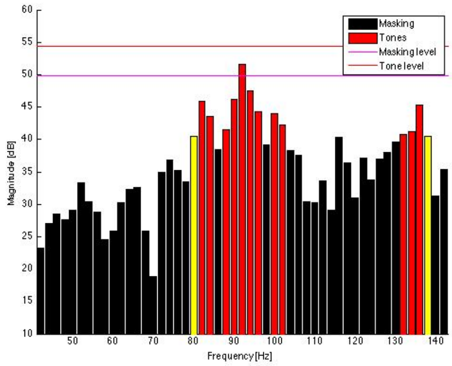
(a) 92 Hz, 21st spectrum



(b) 92 Hz, 34th spectrum



(c) 92 Hz, 42nd spectrum



(d) 92 Hz, 54th spectrum

Figure 48: Identified tones in background noise

7 Discussion and conclusions

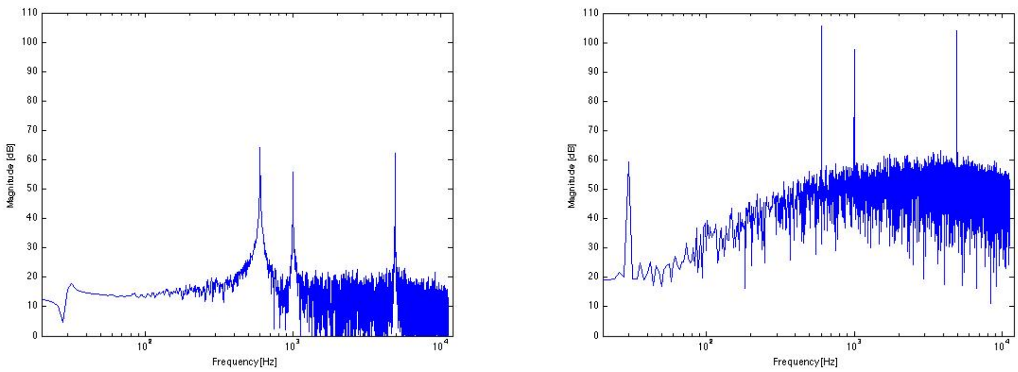
In this section the issues of the analysis made in this work are discussed. In the end the found problems and the discoveries are summarized.

7.1 Discussion

The IEC narrow band tonal noise assessment seems to be by far the most complex compared to the other published analysis methods. Nevertheless the way the standard is presented on paper leaves quite a lot of room for interpretation. In this section the possible issues, which lead to appearance of audible tones in both wind turbine noise and background noise recordings, are discussed.

In order to make sure that the analysis reveals correct audible tones an artificial recording was created. It included four high levelled tones at 30 Hz, 600 Hz, 1000 Hz and 4900 Hz. White Gaussian noise with signal-to-noise ratio of 50 % was added to the signal.

The analysis lists 600 Hz, 1000 Hz and 4900 Hz peaks among several others. Due to Hanning-windowing the 30 Hz peak is attenuated to a level where it does not clearly stand out from the background noise. In figure 49 the entire spectrum of a 10s sample is presented side by side multiplied by a Hanning-window and by a rectangular window. The magnitude proportions of the strongest peaks seem to

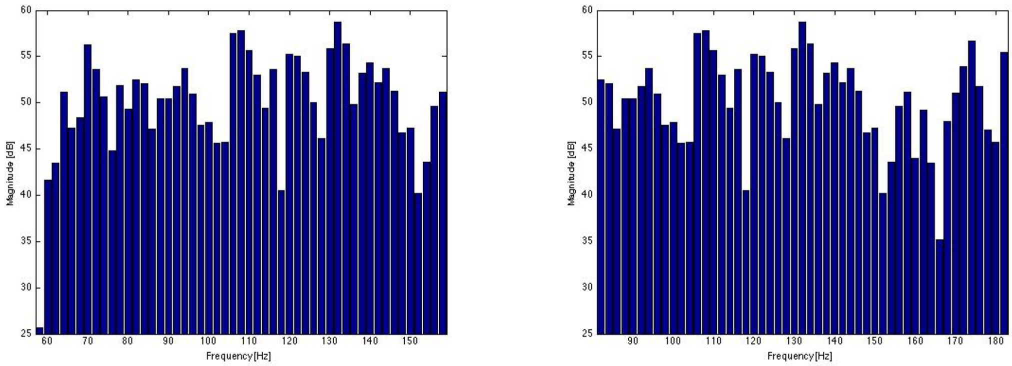


(a) Hanning window (b) Rectangular window

Figure 49: Frequency spectra of test signal

be similar excluding the low frequency region. Though windowing does not provide a solution to the problem of recognizing tones that cannot be spotted clearly from the spectrum.

The standard does not give an exact protocol for handling the occurence of the exact same tone in consecutive critical bands. It is possible for two or more possible tones to have the same frequency selected as the identified peak. As an example in figure 50 is presented two slightly different critical bands from the wind turbine measurement, in which 132 Hz peak has the highest level. Although the levels are the same, tonality value changes due to shifted spectrum. In the standard it is not stated which one is chosen. In this work the one with the highest tonal audibility is chosen and the other is disregarded from further calculations.



(a) Critical band 58-158 Hz (b) Critical band 82-182 Hz

Figure 50: Same identified tone in two different critical bands

Furthermore before final determination of tonal audibility a clean up has to take place. If there are several audibles within a critical band, there is no guideline which one should be chosen. Intuitively it should be the strongest one, but what if there is yet another with even higher level. It is possible to start an iteration for finding the most audible tone and finally choose one, that is outside the initial one's critical band. In table 6 is shown an example of several tonal audibility levels and upper and lower limits for the critical band centered at the given frequency. The 200 Hz tone would be chosen and the others disregarded. In this work the above mentioned procedure is used and the highest value is chosen regardless if it was outside the initial peak's band.

Centre frequency	**Lower limit of critical band**	**Higher limit of critical band**	**Tonal audibility**
68	20	120	-2.3
118	68	168	-1.2
155	104	206	0.3
200	148	252	5.4
248	196	300	3.2

Table 6: Overlapping critical bands with audible tones

In the IEC 61400-11 is mentioned that a tone is audible if its tonal audibility exceeds 0 dB. Still the threshold for reporting a tone is - 3 dB.

With closer inspection of a critical band centered at an identified tone, it can be seen that the uneven distribution of energy throughout the frequency range makes it possbile for a relatively low peaks to be considered as tones. In figure 51 is shown an identified tone in the test signal at 1989 Hz. Several tone lines exist, because of fluctuation of frequency levels in the background noise. Similar can be seen in the spectra presented in section 6.

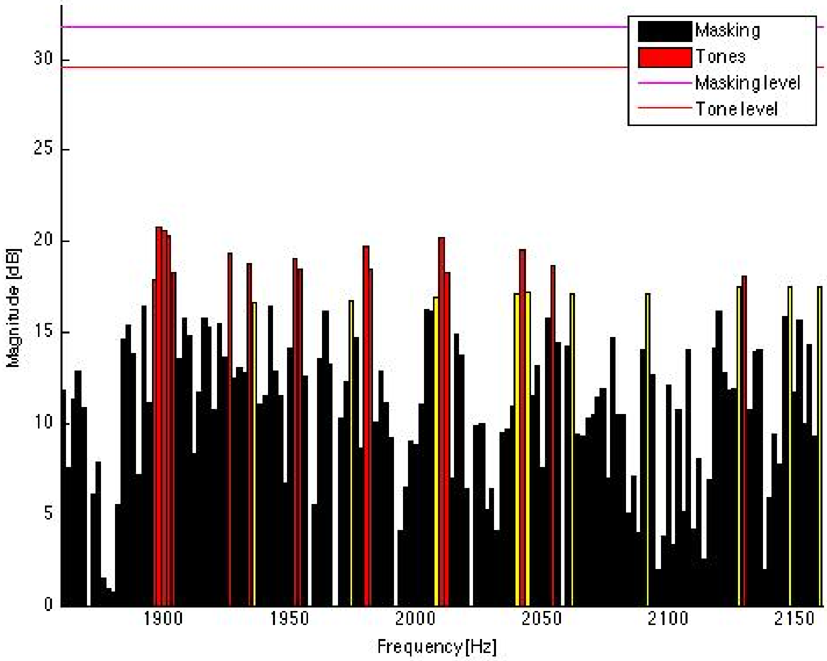


Figure 51: Identified tone at 1898 Hz

Individual tones are not the problem by themselves. More than 20% out of all the measured spectra need to have identified tones of the same origin before the tone is considered as audible. In the 2.1 version of the IEC 61400-11 standard, it was criticized for not ensuring consistency and accuracy in the tonality analysis of strongly non-stationary noise [60]. In the 3.0 version this is fixed by letting the tone wander ±25% of the critical bandwidth. In the example signal's case the audibility threshold is exceeded because of several audible tones around the range in different spectra. The actual audibility of these peaks should be questioned.

A possible solution could be smoothing the spectrum before further calculations. By getting a more even frequency response the random peaks of background noise would affect the determination of spectral lines less. Smoothing basically means that some of the data is filtered by for example a moving average filter. In figure 52 is shown an example of what would filtered spectrum of the test signal look like. The biggest issue would be the loss of data.

Another way to determine the spectral content of a random signal is to calculate the power spectral density PSD. It describes how much power a frequency unit has. The density is possible to calculate from FFT results. [61]

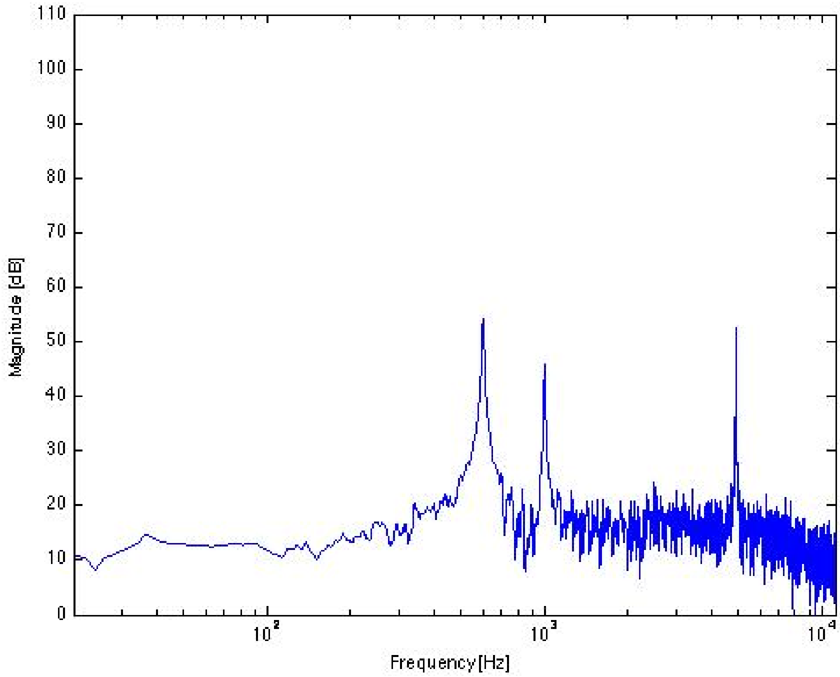


Figure 52: Smoothed spectrum of test signal

It is also possible to calculate the FFT with extreme frequency resolution e.g. 0.05 Hz and post-process the result spectrum. The data could be summed up to bands of 2 Hz, which describes the desired frequency resolution. As seen in figure 53 the above-mentioned way to acquire the test signal's spectrum smoothens the noise significantly.

Critical band has been chosen as the reviewed bandwidth for possible tones. The main idea is that frequencies outside the band do not influence in the audibility of single peaks. There are a few other versions used in similar analysis. First is the fixed bandwidths used in the Joint Nordic Method and second is third octave bands. All three are plotted in figure 54 as a function of centre frequency. They do not differ radically, so contribution of the differences to the analysis could be considered minor.

But what comes to the actual spectrum representation of bands of different length, the accuracy is definitely best with constant 2 Hz bands compared to 12th and 24th octave bands. In figure 55 can be seen how well the FFT method above performs with distinct peaks. Clearly the narrower band is superior to the others. However, better accuracy leads to more complex calculations and ripple in background noise spectrum.

There is no reference to checking if an identified tone is higher than the hearing threshold. Since Hanning-windowing lowers the signal level, it should be tested whether the audibles can actually be heard.

As a final remark it is necessary to shift the frequency spectrum's magnitude

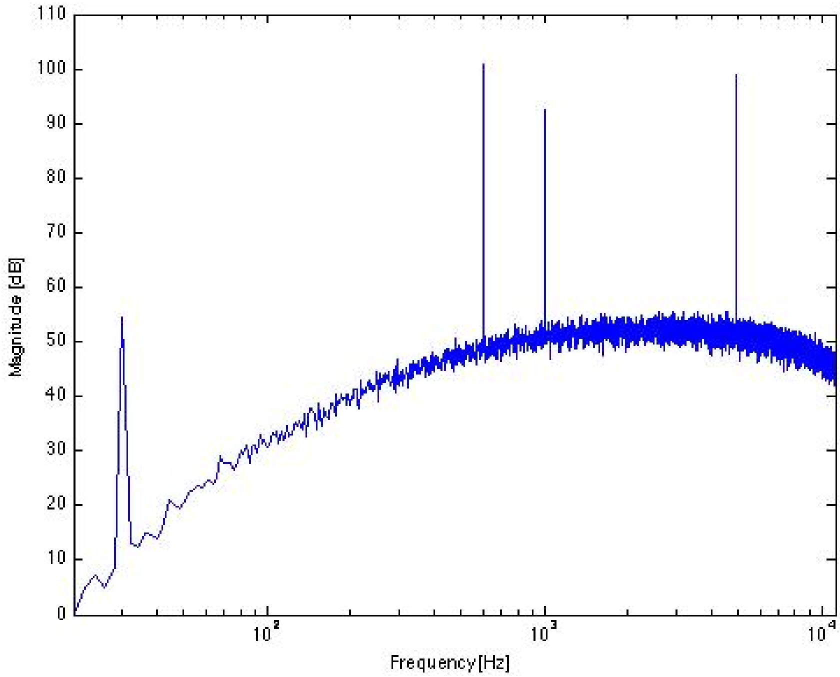


Figure 53: Test signal's spectrum acquired by means of more precise FFT

to positive levels. Although the calculation method is based on determination of differences in the levels, there are operations in between which might lead to false results. For example dividing a negative value makes it bigger, whereas with positive numbers the result becomes smaller.

7.2 Conclusions

As the calculation method of tonality in the IEC 61400-11 is rather complex, though modern computers do not require optimization of models used in calculations. Therefore it is justified to use original curves and formulas for determination of key figures, though the simplified versions do not differ profoundly and the effect could be considered minor.

Equations and the general progress of the analysis is straight forward and well explained. However it leaves room for interpretation, which in worst cases could lead to divergence in results between different implementations of the analysis.

Audibility threshold is not taken into account when assessing the tonal audibility. Differences in levels determine the tonality. It is likely that tones that cannot be heard are not detected, but the signal is not required to be corrected with calibration values to the right level after using the Hanning window. Most frequencies are attenuated and therefore do not correspond to the real life situation where they were acquired.

The implementation of the narrow band spectra seems to be a key cause of

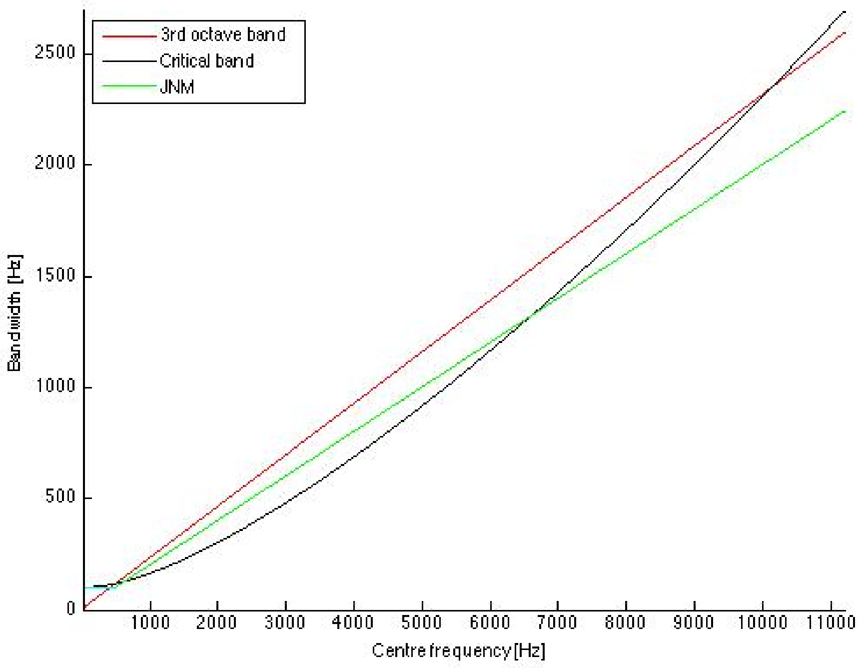


Figure 54: Bandwidths of critical bands of different standards

problems since everything is based on a reliable frequency response. It is assumed that the background noise is evenly distributed. Fluctuation in frequency levels lead to a false discovery of audible tones. More precise review of the results shows that the problem that lead to unlikely results is formation of frequncy response.

Use of FFT is required in the standard. Nevertheless, instuctions how to implement it are left unmentioned. The way used in this thesis is clearly inadequate, as the quantity of tones discovered in the background noise is highly unlikely. The method presented as an alternative in section 7.1 seems to work much better. Looks like the reason for uneven spectral distribution of noise was due to insuffcient frequency resolution of calculated FFT.

The detailed analysis is evolved from simplified versions of determination of tonality. Where third octave bands could not detect varying tones that locate at the edges of two bands, the narrow band method definitely will find them. If tonality cannot be found with this technique, then it is highly probable that none of the others will either, assuming of course that the problem of uneven distribution of background noise in frequency domain is resolved.

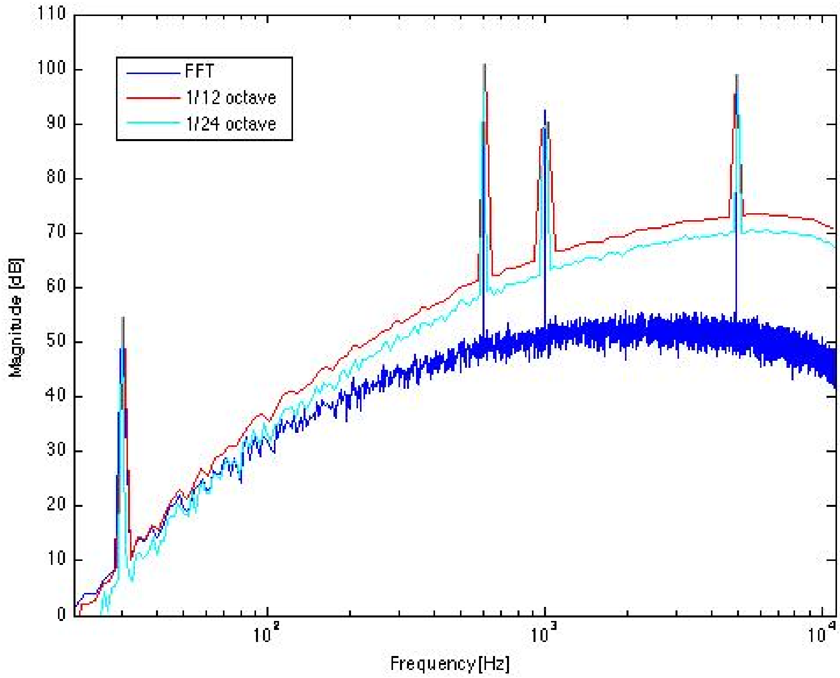


Figure 55: $\frac{1}{12}$- and $\frac{1}{24}$-octave bands compared to FFT

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